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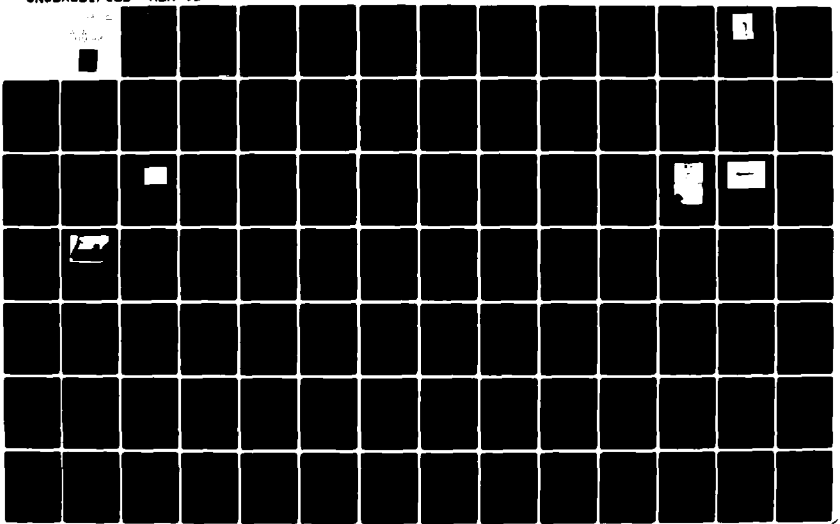

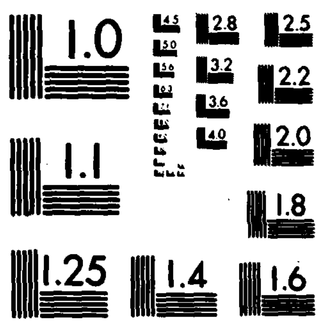

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DEVELOPMENT OF A HIGH ENERGY DENSITY CAPACITOR FOR PLASMA THRUSTERS

FINAL REPORT, [redacted] JUL[redacted]77 — MAY [redacted]80

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FOREWORD

This report was prepared by Maxwell Laboratories for the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California under Air Force Contract F04611-77-C-0045. The objective of the program was the investigation of certain capacitor impregnants and their influence on high energy density capacitors which are employed in spacecraft.

The program was monitored by Lieutenant Michael Brasher of the Liquid Rocket Division. At Maxwell Laboratories, Mr. Allen Ramrus was program manager and technical director. Mr. C. Wayne White was manager of capacitor production and also provided key technical assistance in all aspects of the program. In addition, important contributions were made by Messrs. Paul Hoffman, Robert Cooper and Kurt Haskell. Technical support was also provided by Messrs. Richard Brown and Robert Haug.

A substantial part of this program was conducted at Fairchild Republic Company (FRC). Dr. William Guman managed the first phase of the subcontract at FRC and Dr. Dominic Palumbo directed the subsequent portions. They were assisted by Mr. Martin Begun throughout this effort.

This report has been reviewed by the Technical Information Office/TSPR and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations. This technical report has been reviewed and is approved for publication; it is unclassified and suitable for general public release.

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This report presents the results of a technology program directed towards the development of a long-life, high-energy-density capacitor for application in spacecraft. The capacitor has low inductance (<20 nH) and an energy density up to 40 J/lb. Voltage vs. life curves are shown which indicate this capacitor will withstand over 10^7 discharges when operated at rated voltage of 2.2 kV.
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Materials were employed in this capacitor which should render it resistant to damage from radiation. To attain radiation resistance and high-energy density, Kraft tissue was successfully excluded from the winding which is composed principally of K-F polymer and aluminum foil. Various impregnants were tested and the most successful was silicone oil.

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SECTION 1

INTRODUCTION

Maxwell is pleased to present the Air Force Rocket Propulsion Laboratory with this final report on the Development of a High-Energy-Density Capacitor for Plasma Thrusters. This program was directed towards the advancement in the technology of pulse discharge capacitors of a type which are suitable for spacecraft. This space application results in stringent requirements such as the relatively high energy density (ρ_ε) of about 88 J/kg (40 J/lb) in capacitors with discharge life over 10^7 discharges. Substantial progress in capacitor state-of-the-art has accrued from research on this type of capacitor. A photograph of the capacitor is shown in Figure 1-1, and the specifications are summarized in Table 1-1.

The capacitor plays an essential role in the operation of the pulsed plasma thruster. This role can be discussed by considering the peak power flow through the power conditioning circuit to the thruster. The power conditioner converts the relatively low power which is obtained from solar cells or batteries to the high voltage required by the plasma thruster. The power conditioner is not capable of providing the high peak power which the thruster requires. This high peak power is provided by the capacitors which are mounted in a low inductance circuit of which the plasma thruster is an integral part. Thus, the peak output power into the plasma load is on the order of a hundred megawatts, although the power which flows into the capacitor bank is about 180 W. The high pulse power lasts for a few μs whereas the power flow into the capacitors is constant during the time the thruster system is operating.

In several key respects, this program was built upon previous developments in the field of high energy density

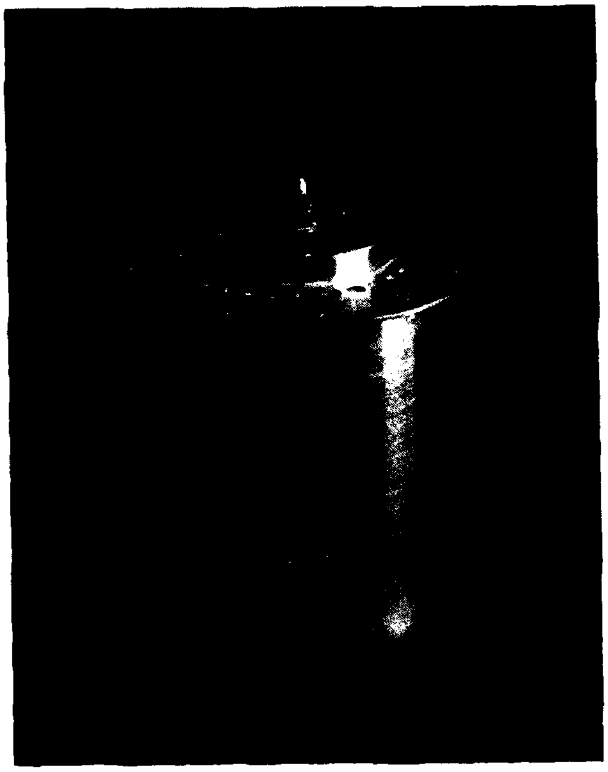

Figure 1-1. The 80 μF capacitor tested during this program. Case diameter is 10.5 cm (4.14 in.).

Table 1-1. Capacitor specifications and goals

Specification	Goals
Energy	190 J at 2.2 kV
Voltage	2.2 kV ±1%
Voltage reversal	25%
Capacitance	80 μF + 10% - 5%
Inductance	15 nH
Loss factor	0.010 Goal 0.013 (maximum at 25°C, 120 Hz)
Peak current	30 kA
Initial dI/dt	10^{10} A sec^{-1}
Pulse Rate	0.17 Hz (normal) 1.00 Hz (maximum)
Burst duration	Indefinite
Capacitor temperature Range	-20°C to +50°C (design) -35°C to +70°C (goal)
Ambient pressure	10^{-4} Torr
Radiation environment	Unspecified intensity
Life	10^{7} shots
Reliability	Not specified
Gross energy density	88 J/kg (40 J/lb)@ 2.2 kV
Weight	4.75 lbs
Shape	Cylindrical
Dimensions	10.5 cm (4.125 in.) OD, 18.4 cm (7.25 in.) length

capacitors. Table 1-2 lists programs which have preceded the present one. The high value of energy density attained during this program is, in part, due to the use of polyvinylidene fluoride film as the capacitor dielectric. This material which is commonly referred to as K-F polymer is of particular interest to the capacitor industry because of its high dielectric constant of about 10. At this time the Kureha Corporation of Japan is the sole supplier. Under contracts with the Air Force, Maxwell and other laboratories have studied the application of this material to capacitors. Conventional films such as polypropylene or polyester have relative dielectric constants in the range of 2 to 4. Most impregnants have dielectric constants in that range also. At equal stress, a film with dielectric constant of about 10 has over three times the energy density of conventional films. However, prior to this program, it was unclear whether reliable, paper-free capacitors, which included a film whose k exceeded that of the impregnant could be successfully constructed. In part, the difficulty in thoroughly impregnating a paper-free capacitor was thought to pose a serious limitation. However, by adapting vacuum impregnation techniques which were previously developed for other types of paper-free capacitors, Maxwell successfully achieved a thorough impregnation.

In addition to doubts about impregnation, other questions on this construction required resolution. For example, the combination of a film with high k and an impregnant with low k is not, a priori, an acceptable construction because of the presence of nonuniformities in the electrostatic field within the winding. In principle, when this construction is subjected to low voltage, as it is during the initial stage of charging, the stress tends to be higher in the impregnant layer than in the dielectric film by the factor k_F/k_I. Then, as voltage is increased, a complex process of corona and charge migration occur in the impregnant which in effect short-circuits the

Table 1-2. Previous development programs on high density capacitors

Year	Capacitor	Construction	Major Design Parameters
1976	FRC/RCA 15 μF	Mylar/MIPB	All film vacuum environment large temperature range
1977	AFRPLS/FRC 60 μF	K-F/Paper/ Castor Oil	Vacuum, large temperature range
1976 to Present	FRC	Mylar/ Silicone Oil	All film
1978	RCA, 15 μF	Mylar/MIPB	All film, vacuum, large temperature range
Present Tests	AFRPL, 80 μF	K-F polymer/ Silicone Oil	Vacuum, large temperature range
		K-F-polymer/ MIPB	all film

liquid. This process must transfer nearly full capacitor voltage to the dielectric film. This redistribution of voltage in constructions which employ high K-F polymers and low k impregnants had an unknown influence on capacitor life and, therefore, life tests were an important part of this program.

During this program three dielectric fluids were tested which had dielectric constants less than that of K-F polymer. These were tricresyl phosphate (TCP), silicone oil (DC-200) and monoisopropyl biphenyl (MIPB). A fourth fluid, Diallyl Phthalate (DAP) was also tested which had a constant equal to that of K-F polymer. Discharge life curves were generated to clarify the influence of dielectric constant on life. Based on extrapolations from test voltages which exceeded the rated capacitor voltage, K-F polymer capacitors impregnated with silicone oil in a paper-free capacitor were found capable of meeting the goal of 10^7 shots at 2.2 kV. Capacitors impregnated with monoisopropyl biphenyl (MIPB) were only marginally capable of meeting the goals. Both of these liquids were of low dielectric constant. DAP, the impregnant whose constant equalled that of K-F polymer was eventually rejected because of electrophysical effects such as film wrinkling and roughening which indicated abnormal interaction between the liquid and the K-F polymer. TCP was also rejected because it, too resulted in more of those interactions than did the MIPB and silicone oil.

In addition to the study of this unique dielectric film, the program requirements called for use of a special stainless steel capacitor can which is capable of withstanding the variation of internal pressure caused by the temperature changes during operation of this capacitor in a vacuum environment. This capacitor can was developed under previous contract by Fairchild Republic Corporation.

SECTION 2

PROGRAM SUMMARY

Virtually all impregnants in use by the capacitor industry have relative dielectric constants in the range of two to four. An important aspect of this program was the evaluation of liquids with higher dielectric constant and which also have physical properties suitable for an impregnant. To accomplish this investigation, the chemical literature was surveyed and a list of about 250 liquids with $k > 5$ was compiled. (See Appendix A.)

Four groups of scaled capacitors employing each of the four candidate impregnants were manufactured for discharge life tests. These capacitors were scaled down to 6 μF from the required 80 μF to reduce cost of samples.

The original plan called for one impregnant to be selected from the four. Then, full-scale tests on 80 μF capacitors impregnated with that impregnant were to be conducted. However, at the end of the scaled tests, two impregnants appeared approximately equivalent which resulted in the manufacture of two sets of capacitors, followed by the final testing. This four-task program plan is summarized in Table 2-1.

As indicated in the specifications, the discharge life goal of 10^7 discharges at the rated charge voltage of 2.2 kV is required. At a shot-rate of about 1 Hz at rated voltage, a single test would require nearly 3000 hours, which would require months to accomplish. The approach taken throughout this program was to accelerate the test by using increased charge voltage. Life is known to be an extremely sensitive function of charge voltage. Operating at a higher voltage and at reduced shot-rate to control heating results in the opportunity to acquire significant amounts of discharge life

Table 2-1. Program Summary

Phase	Task
1.	Literature survey - Primary object: List liquids with $k > 5$.
2.	Scaled tests (a) Select four impregnants. (b) Manufacture and test 6 μF samples
3.	Manufacture final 80 μF capacitors. (a) Silicone oil impregnant in stainless steel cases. (b) MIPB impregnant in standard cases.
4.	Test final capacitors. (a) Test silicone impregnated capacitors at room temperature (25°C) and at temperature extremes (-20°C) and + 50°C). (b) Test MIPB-impregnated capacitors at room temperature.

data points on numerous samples in a relatively short time. The disadvantage of this approach is that a discharge life versus charge voltage curve must be generated to allow extrapolations to the final voltage. A primary program objective, therefore, was the determination of this discharge life versus voltage relationship. Therefore, in Part 2 of the program, life versus voltage curves were generated for 6 μF capacitors. During Part 4, they were generated for 80 μF capacitors.

SECTION 3

IMPREGNANT SELECTION

The literature survey* was conducted by means of a computerized search of the chemical literature. Only materials with $k > 5$ were called forth, although other important physical properties were compared, such as phase-change temperatures, resistivity, vapor pressure and viscosity. Liquids with properties like those of cyanoethyl sucrose and castor oil were rejected because they tend to freeze at or above $\cong -20^{\circ}C$ which approaches the lower limit of capacitor operation. In the process of accepting or rejecting liquids, intuition played an important part, e.g., liquids which may freeze or crystallize were rejected because a phase change within the capacitor probably would result in premature failure due to creation of impregnant-free voids.

Numerous materials were listed which had high vapor pressure such as the organic solvents. These materials were rejected because they would require special handling in order to ensure adequate impregnation. Additional research in that area would have been required, although in a future program the difficulty in handling these materials may not be as serious a limitation. (High dielectric constant in organic liquids was frequently associated with high vapor pressure.)

The Arochlor impregnants which are among the environmentally restricted polychlorinated biphenyls (PCB) were listed but were not selected for testing during this program because of the difficulty in obtaining them and other candidates appeared equally attractive. Ethylene glycol and

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* The computerized literature search was conducted by Fairchild Republic Corporation under contract to Maxwell.

several high k (>30) aqueous solutions were considered but their resistivity was too low, being $10^7 \Omega$ cm, whereas about $10^{11} \Omega$ cm is considered minimum for the slow-charged capacitors of present interest. Low resistivity would be unacceptable because excessive heat would be generated during the five to ten second charging period. This heating would be localized around the foil edges, would create gas and early failure.

The conventional liquid impregnants were also investigated, such as tricresyl phosphate (TCP, k = 6.9) and silicone oil. Finally, a group of four liquids were selected, two with the relatively high k of about seven or greater and two with low k, less than three. These materials are shown in Table 3-1. The entire listing was not exhaustively studied to the point where all physical properties of each liquid were obtained and analyzed. Time limitations prevented so detailed a study. There may very well be a superior material which escaped selection because certain physical properties were grossly irregular compared to more common impregnants, its properties unknown or were difficult to unearth. The listing still serves as a source of ideas for new impregnants for future experiments.

As a capacitor impregnant, the least-known is diallyl phthalate. A manufacturer specification for this material is shown in Appendix B. This impregnant has a dielectric constant of ~10 which is the highest tested during this program. It is relatively common in its polymer form and is used in transformers.

Table 3-1. Impregnants selected for scaled capacitor tests.

	Impregnant	k
1	Tricresyl Phosphate (TCP)	6.9
2	Monoisopropyl Biphenyl (MIPB)	2.5
3	Silicone Oil (DC-200)	3.6
4	Diallyl Phthalate - monomer (DAP)	10.0

SECTION 4

DESIGN CONSIDERATIONS

4.1 FULL-SIZE 80 μF CAPACITOR CIRCUIT

The design objective of the test circuit is the simulation of the voltage and current waveshape which occurs when the capacitors are used in plasma thrusters. In that application the final 80 μF capacitors are charged to the rated 2.2 kV, discharge with a peak current of about 30 kA, experience an initial $\dot{I} \approx 10^{10}$ A/s and have 25% current reversal. (These parameters correspond to a discharge period of about 20 μs.)

If these capacitors were tested at their rated voltage, years would be required to complete the tests. An important program objective is to accelerate the test program to accomplish it within schedule limitations. Therefore, higher than rated voltages are applied to the test capacitors to shorten their discharge lives. When these higher voltages are applied, I and $\hat{I}$ are also increased in direct proportion to voltage while the discharge frequency and reversal remain constant. Previous capacitor life experiments performed at Maxwell and other laboratories have shown life proportional to $V^{-\alpha}$ where V is charge voltage and α a constant. This dependence was assumed in the accelerated experiments performed during this program. Because of this acceleration, it is necessary to establish the discharge life versus voltage to allow extrapolation of life to the 2.2 kV rated voltage in order to determine whether or not the 10^7 shot specification will be attained. The extrapolations are described in the following section.

To reduce capacitor costs during this phase of the program, a scaled capacitor was employed; 6 μF were selected as a reasonable compromise between the desire to maximize sample size to achieve realism, and the desire to reduce unit costs. To preserve good simulation, at given voltage, the peak current was reduced through the capacitor in direct proportion to the capacitance. For example, since the 80 μF capacitor passes 30 kA at 2.2 kV, the peak current specification was reduced to 2.3 kA at 2.2 kV in the 6 μF tests. Discharge period and reversal remained the same for 6 μF as for 80 μF capacitors. This relationship was found in many previous experiments performed at Maxwell.

Required circuit parameters to meet these specifications were established by first using lumped-constant analysis. Then, adjustments were made in either circuit resistance or inductance once the circuit was in operation.

a. Circuit Resistance and Inductance. To establish the required electrical parameters for 80 μF tests, consider the simplified circuit of Figure 4-1.

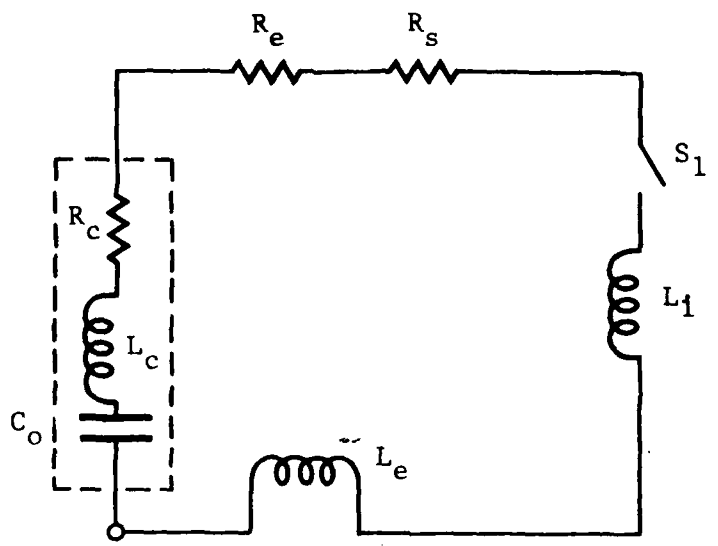
The requirement for 25% reversal causes the total circuit resistance R_T to be given by

$$R_{TOT} = 0.4\ R_c$$

where R_c is critical damping resistance, $2\sqrt{L_{TOT}/C_2}$. The relation between rated charge voltage V_o and rated peak current, V_o depends only on reversal and for 25% reversal, is given by:

$$\hat{I}_o = 0.6\ \frac{V_o}{\sqrt{L_{TOT}/C_o}}$$

Combining these two equations allows L_{TOT} and R_{TOT} to be calculated.



C_o	Test capacitors (80 μF)
L_c	Internal capacitor inductance (15 nH)
R_c	Internal capacitor effective resistance (10 mΩ)
R_e	External resistance composed of nichrome strip
R_s	Stray resistance in connections and switch (10 mΩ)
L_i	Switch inductance
L_e	Inductance external to capacitor and switch

Figure 4-1. Discharge circuit of test capacitor.

$$R_{TOT} = 0.4\ R_c = 0.8 \sqrt{L_{TOT}/C_o}$$

$$\hat{I}_o = \frac{0.6\ V_o}{\sqrt{L_{TOT}/C_o}}\ , \quad \sqrt{L_{TOT}/C_o} = \frac{0.6\ V_o}{\hat{I}_o}$$

Eliminating the square root yields:

$$R_{TOT} = 0.8 \times 0.6 \frac{V_o}{\hat{I}_o} = 0.48 \frac{V_o}{\hat{I}_o}$$

For rated V_o and $\hat{I}_o$ of 2.2 kV and 30 kA respectively,

$$R_{TOT} = 35\ m\Omega$$

Circuit inductance for 80 μF capacitors is:

$$L_{TOT} = C_o \left(\frac{0.6\ V_o}{\hat{I}_o}\right)^2 = 80\ \mu F \left(\frac{0.6 \times 2.2\ kV}{30\ kA}\right)^2$$

$$L_{TOT} = 155\ nH$$

In practice, this inductance is obtained with a low inductance strip line, about 1 ft long which connects the capacitor to the spark gap. A nichrome resistor is connected to this strip line as shown in Figure 4-2. This load resistance is calculated below.

b. Resistive Load. Total circuit resistance is composed of equivalent series resistance in the capacitor R_i stray resistance in the spark gap, wires and connections, and that of the nichrome load. The sum of resistance excluding

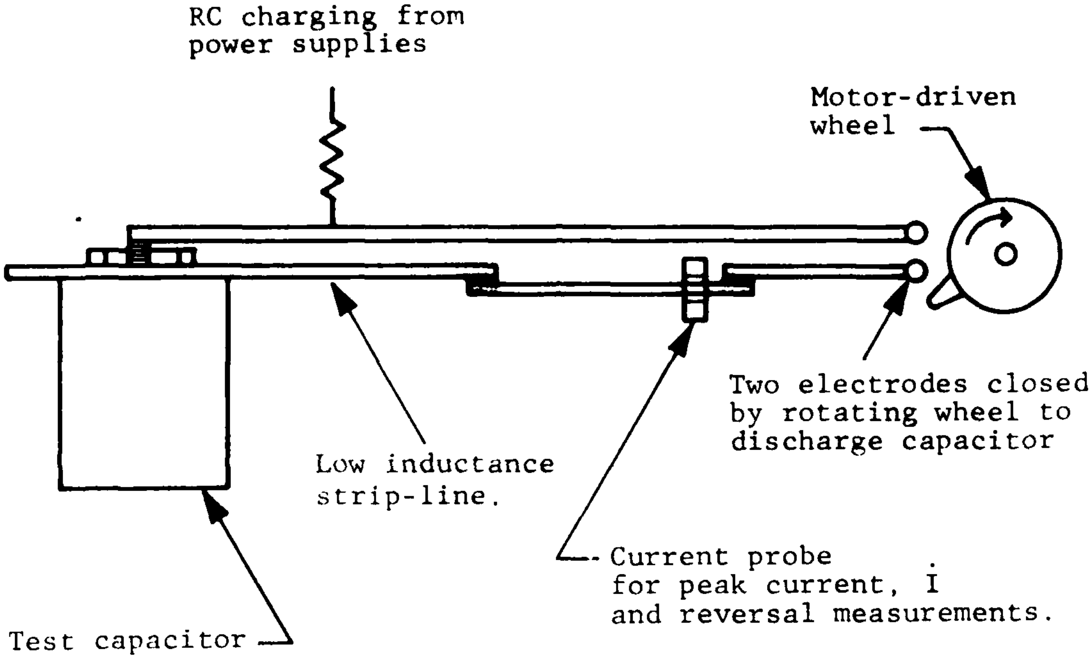


Figure 4-2. Schematic of a capacitor discharge circuit to meet reversal and high current requirements.

the load is 20 mΩ; therefore, 15 mΩ is required in the nichrome resistor. For example, a pair of nichrome strips, each with one-half in. width and 0.020 in. thickness would have a length given by

$$\ell = \frac{AR}{\rho} = \frac{2 \times (\tfrac{1}{2}\text{ in.}) \times (0.020\text{ in.}) \times 15\text{ m}\Omega \times (2.54\text{ cm/in.})^2}{110\ \mu\Omega\text{-cm}}$$

$$= 18\text{ cm (7 in.) in length.}$$

At the 60 kHz discharge frequency, this simple resistance calculation is accurate because the skin depth at this frequency is 2 mm, substantially larger than the nichrome thickness of 0.5 mm.

This length of nichrome is set in a low inductance geometry and is included in the strip-line buswork. In practice, the capacitor and circuit resistances are not precisely known and the nichrome resistor is trimmed until the 25% current reversal is obtained.

c. Rate of Rise. An additional specification calls for a minimum rate of rise of 10^{10} A/s. For early time in an oscillatory circuit (regardless of resistance) $\dot{I}$ is given by the equation:

$$\dot{I} = \frac{d}{dt}\,(I_o \sin \omega t)$$

and

$$\hat{\dot{I}} = I_o\omega = \frac{I_o 2\pi}{T} .$$

or,

$$\hat{\dot{I}} = \frac{I_o}{\sqrt{L_{TOT} \cdot C_o}}$$

For L_{TOT} = 155 nH, C_o = 80 μF and I_o = 30 kA, $\hat{I} \sim 10^{10}$ A/s which meets the specification indicated in Table 4-1.

4.2 SCALED CAPACITOR CIRCUIT

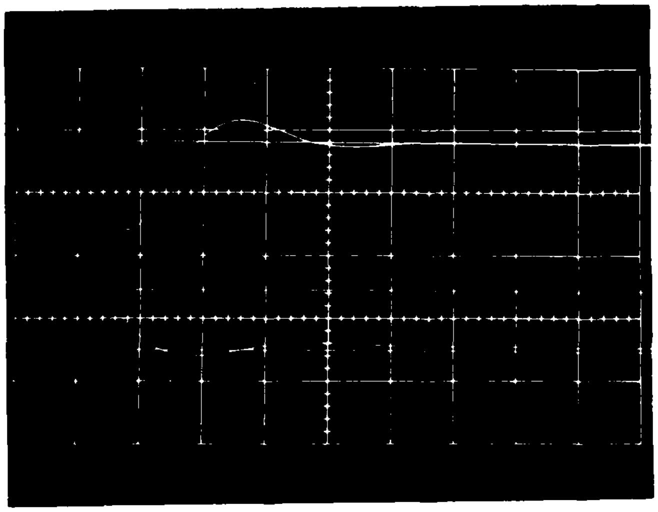
With these parameters established for the 80 μF tests, the circuit elements for the 6 μF scaled tests are derived in the same way. The peak current is reduced to maintain constant current density in the winding. Therefore, rather than 30 kA at 2.2 kV, the 6 μF capacitors require 2.3 kA. The same ringing period and 25% reversal described above for the 80 μF tests are used in these scaled experiments. Figure 4-3 shows a typical current and voltage waveform for a 6 μF capacitor.

Capacitor temperature is monitored by connecting a thermocouple to the capacitor case. The output is connected to a chart recorder for continuous monitoring during the test. The scaled capacitors were immersed in a bath of transformer oil. A fan was placed near the oil, both to circulate air and maintain constant equilibrium temperature of about 38°C (100°F).

V_{chg} = 5 kV

5 kA/div.

5 kV/cm



5 μs/cm

Figure 4-3. Typical current and voltage diagnostic waveforms showing 25% current reversal in 6 μF test capacitor.

(a) Circuit current as measured with Pearson probe.

(b) Capacitor voltage measured in a Teletronics high-voltage probe.

SECTION 5

SCALED TESTS

Scaled experiments on 6 μF capacitors were conducted in order to obtain familiarity with the performance of K-F polymer capacitors impregnated with each of the four impregnants. The test setup allowed four capacitors to be tested simultaneously in a multi site test configuration (Figure 4-2).

The same current waveshape, to be employed in the final 80 μF units, was employed in these scaled tests. One factor which was not similar, however, was the charging waveform. In the final experiments, as in the actual thruster, the charging waveform rises continuously until the discharge transient occurs. In these scaled tests, the charging voltage rises in about three seconds to the final dc value, then remains at that voltage until discharge. In this way, all capacitors mounted to the multi site switch are charged to the same value and when one fires, the others remain at full charge until they, in turn, are discharged. Therefore, the 6 μF capacitors have dc stress applied for a longer duration for each discharge than do the 80 μF capacitors in actual operation. This is viewed as one disadvantage in multi site tests because the effect of this dc stress is unknown. For this reason, the 80 μF capacitors tested during this program were tested singly with a charging waveform which closely simulated the actual one.

5.1 TRICRESYL PHOSPHATE (TCP)

The scaled tests were useful in selecting the film and foil thicknesses. A typical set of experiments is plotted in Figure 5-1 in which the discharge life of capacitors made with various film thicknesses is shown. This selection process involves trade-offs; thin films (i.e., below 9μ) tend to have increased probability of hole density due to imperfections in

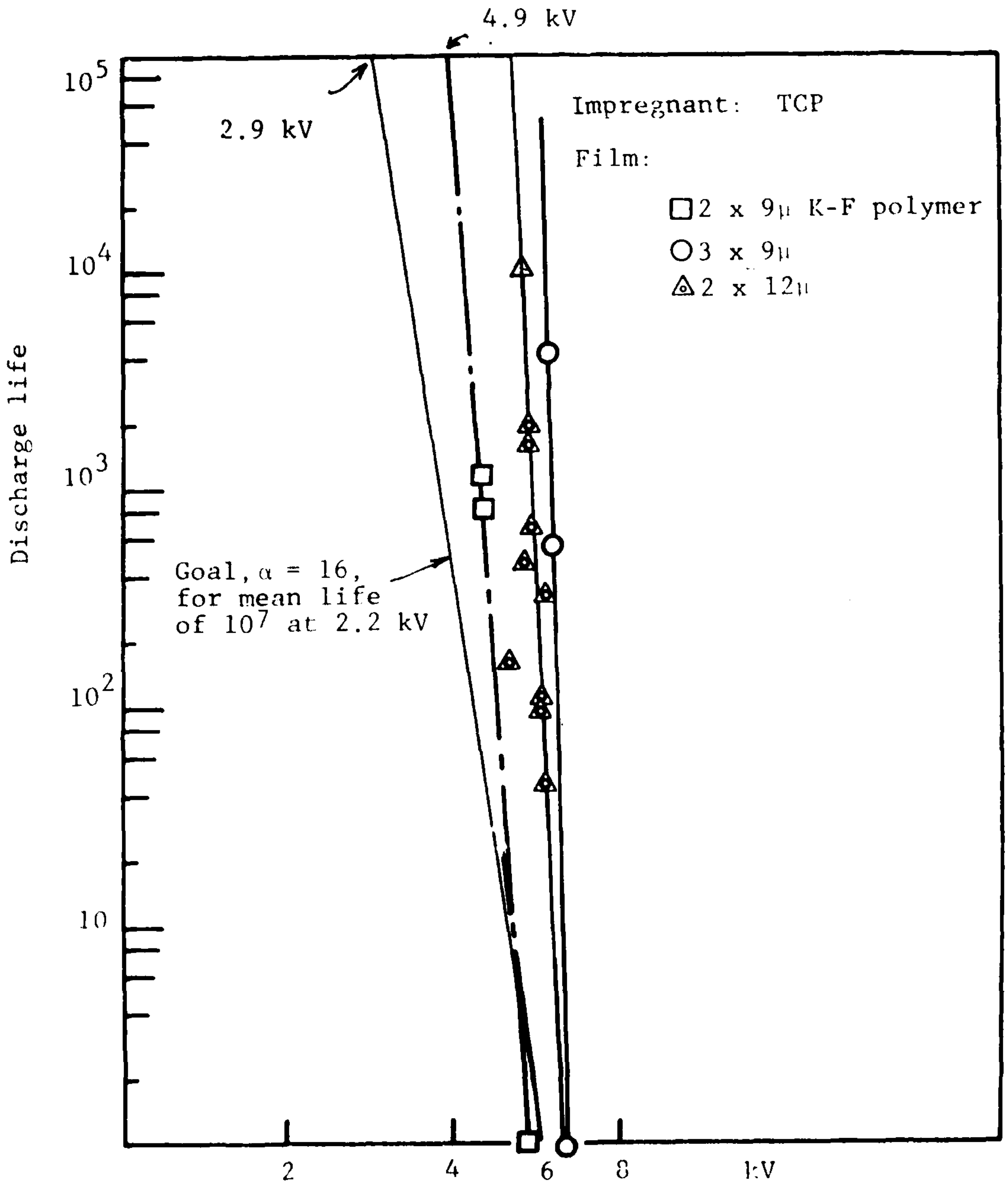


Figure 5-1. Shot life versus charge voltage for 6 μF capacitors impregnated with Tricresyl phosphate (TCP) with film thickness as a parameter.

the manufacturing process. However, the effect of a hole in a multi-layer package containing three films is less than if only one or two films constitute the barrier between electrodes. On the other hand, larger numbers of thinner films are more difficult to thoroughly impregnate than fewer thicker films. Analysis of data of this type did not result in a clear indication that two sheets of 12μ were better or worse than three of 9μ film. The two 12μ films were judged slightly superior because it created a thinner sandwich than the three 9μ films, thereby providing larger energy density which appeared capable of meeting the program goals.

The line drawn on the left of the data points shows the line along which the data must lie in order to meet the minimum goals of the program. At this point it appears the 6 μF capacitors have longer lives than that required to meet the goals. These curves provided a guide to capacitor construction, but do not allow accurate estimates of discharge life for the full size units. The test conditions are somewhat different than that encountered in full scale tests, as described above and the capacitor area is different. It is expected that capacitor life will decline with increased area because larger area creates more potential failure sites. Also, failure mechanisms which are caused by mechanical forces developed in the charged winding are different in the two cases, and may contribute to reduced life in larger windings. Nevertheless, the scaled tests provided important insights into capacitor impregnation and construction which enabled high quality full size windings to be wound subsequently.

5.2 MONOISOPROPYL BIPHENYL (MIPB)

The scaled tests with MIPB as an impregnant were conducted on 2 x 12μ capacitors at 5 kV. These data fell on the same line as did the TCP curve corresponding to 2 x 12μ films. However, the MIPB data were closely grouped, which is an attractive feature for long-lived, highly reliable capacitors. Considerable motivation existed to have MIPB succeed because of its well known resistance to damage from irradiation. However, the data indicated it was approximately equivalent in performance to TCP. Figure 5-2 shows a group of four MIPB failures.

5.3 DIALLYL PHTHALATE-MONOMER (DAP)

This impregnant was initially thought to be the most attractive candidate because of its high dielectric constant. The results did not show success, however, because of the large scatter in the sample life. Several DAP impregnated samples failed on charge at voltages less than those of the other samples; a few of the samples had lives comparable to the other samples. (A set of 5 kV data is shown in Figure 5-2.)

5.4 SILICONE OIL

Silicone oil appeared to be the best material employed during this program. It resulted in some of the best discharge lives obtained to date and the winding survived without severe physical degradation, as evidenced by the autopsy after failure. Also, the silicone impregnated capacitors appeared to fail in a relatively tight grouping (as shown in the 5 kV tests, Figure 5-2.

To estimate the performance of this material in larger capacitors, a group of four 30 μF capacitors were manufactured and tested at 4.5 kV. The discharge lives are shown in the inset of the Weibull plot of Figure 5-3. The Weibull plot provides estimates of reliability versus discharge life. In this context, reliability means the expected percentage of surviving units out of a tested population. For example, the graph indicates a characteristic life, L(0.37), of 8000 discharges. (L(0.37) corresponds to a reliability of 37%.) If

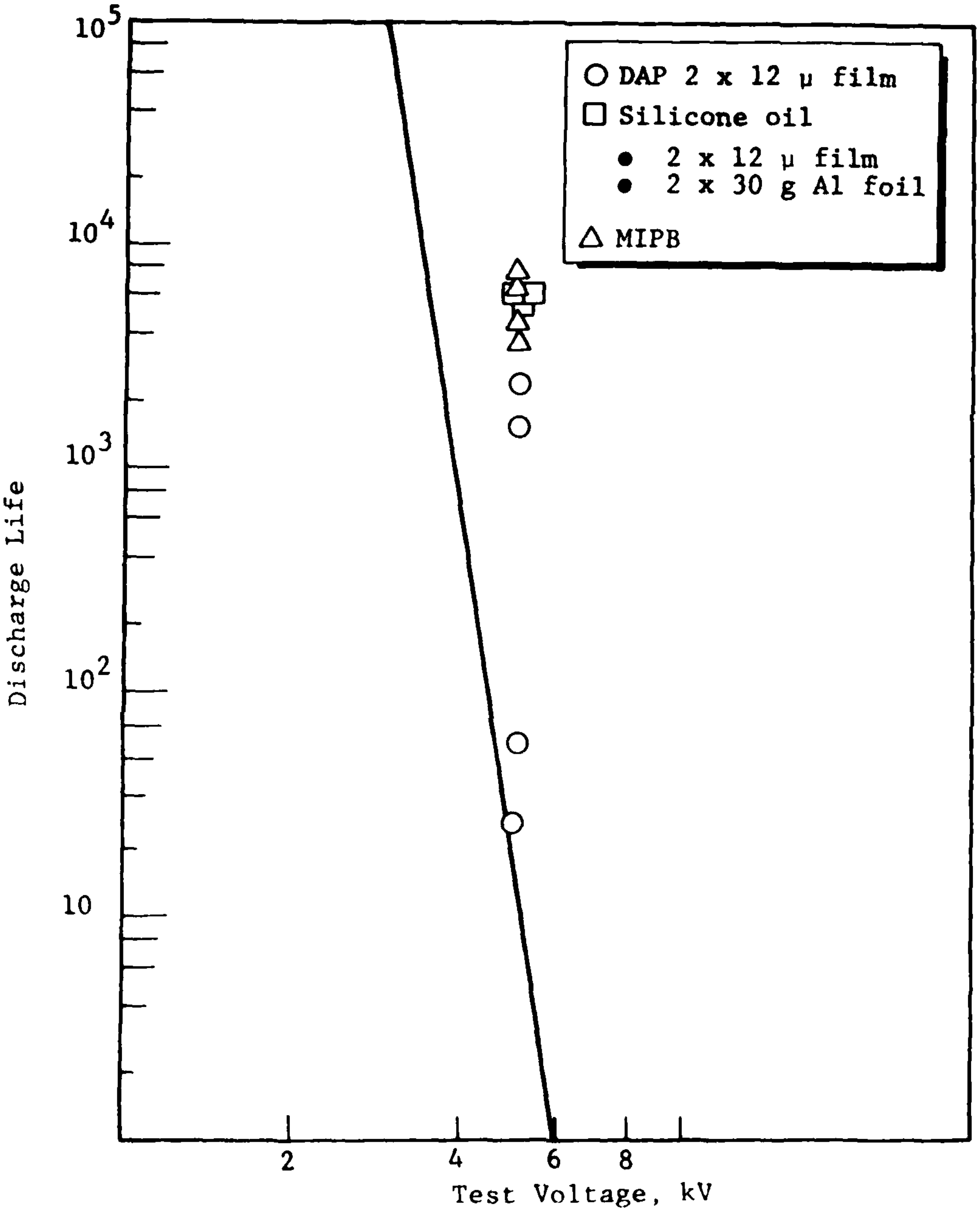
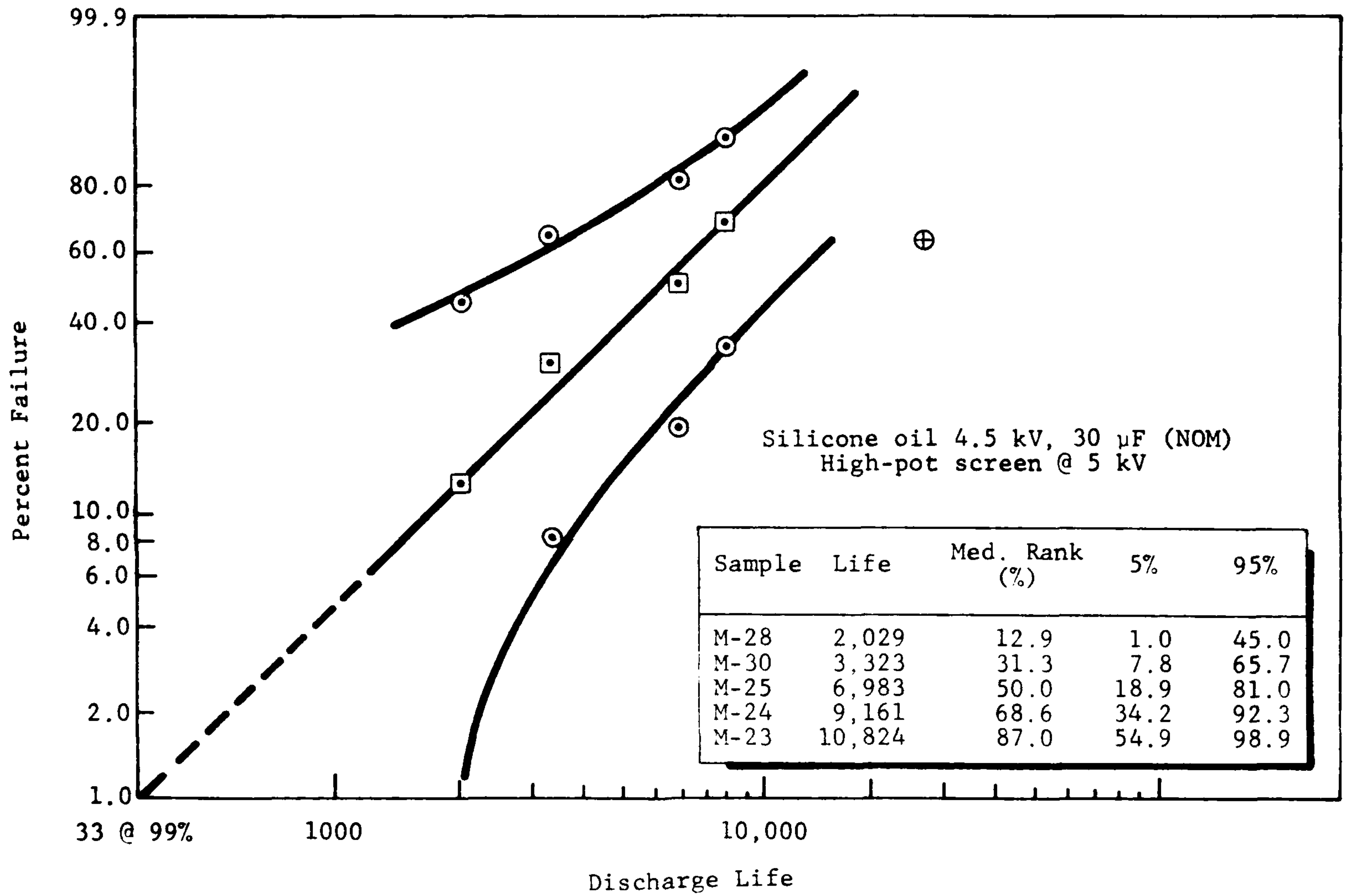


Figure 5-2. Shot life versus charge voltage for 6 μF capacitors impregnated with MIPB, DAP and silicone oil.



Sample	Life	Med. Rank (%)	5%	95%
M-28	2,029	12.9	1.0	45.0
M-30	3,323	31.3	7.8	65.7
M-25	6,983	50.0	18.9	81.0
M-24	9,161	68.6	34.2	92.3
M-23	10,824	87.0	54.9	98.9

Figure 5-3. Weibull plot of 30 μF K-F polymer capacitors impregnated with silicone oil.

this were extrapolated to 2.2 kV by means of the equation:

$$L_2 = L_1 \ (V_2/V_1)^{-\alpha}$$

using α- of 16, the slope of the goal curve, the characteristic life would be 7.5 x 10^8 discharges. Many of the scaled tests had slopes which exceeded 16. The larger slopes would result in predictions of longer capacitor life; therefore, a conservative estimate is chosen. If the Weibull plot were extended to the 99% reliability (1% failure) line, the life would be 330 discharges at 4.5 kV. At 2.2 kV this would provide 3 x 10^7 shot discharge life, assuming the above exponential dependence of life on voltage.

The sparcity of data results in wide confidence bands around the plotted reliability versus discharge life curve. Within the 90% confidence limits, lines which could be drawn to the left of the data would fall short of the 10^7 shot goal. Therefore, encouraging though this data is, more data points are required for confirmation. Maxwell proceeded to 80 μF tests with silicone oil on the basis of these results.

5.5 ELECTROPHYSICAL EFFECTS

One major factor used in assessing the performance of an impregnant is the physical appearance of the foils and films when the capacitor is disassembled after failure. For this program, the underlying objective of accelerating discharge lives by employing higher-than-rated voltage is to estimate life after years of operation at relatively low shot rates. If electrophysical effects indicate lack of compatibility between the materials, it is unlikely the predictions will be valid. Therefore, careful attention was directed towards the compatibility of materials and this factor formed an important basis for comparison of the various materials. For example, TCP was found to result in more severe wrinkling of the K-F polymer than did the MIPB.

Figure 5-4 shows a TCP-impregnated winding. The foil shows considerable distortion, yet the failure occurred in a relatively clear area (Figure 5-4b). The body-failure (off-edge) is the typical location for failures throughout this program. For comparison, Figure 5-5 shows a silicone-impregnated winding with its relatively clear surface condition.

The dialyl phthalate (DAP) had the worst wrinkling effect on the K-F polymer, whereas silicone oil showed good compatibility. Silicone oil and MIPB were judged approximately equivalent although, qualitatively, silicone oil was judged slightly superior. Where discharge lives were equivalent, this qualitative judgement provided the basis for discriminating against a material. DAP was set aside because it had severe electrophysical impact and very erratic discharge life. Therefore, the leader in this competition was silicone oil and MIPB was in second position.

Based on these observations, the major portion of the succeeding program was directed at the testing of capacitors impregnated with silicone oil. Additional tests on 80 μF capacitors impregnated with MIPB was also carried out on windings installed in conventional steel cans.

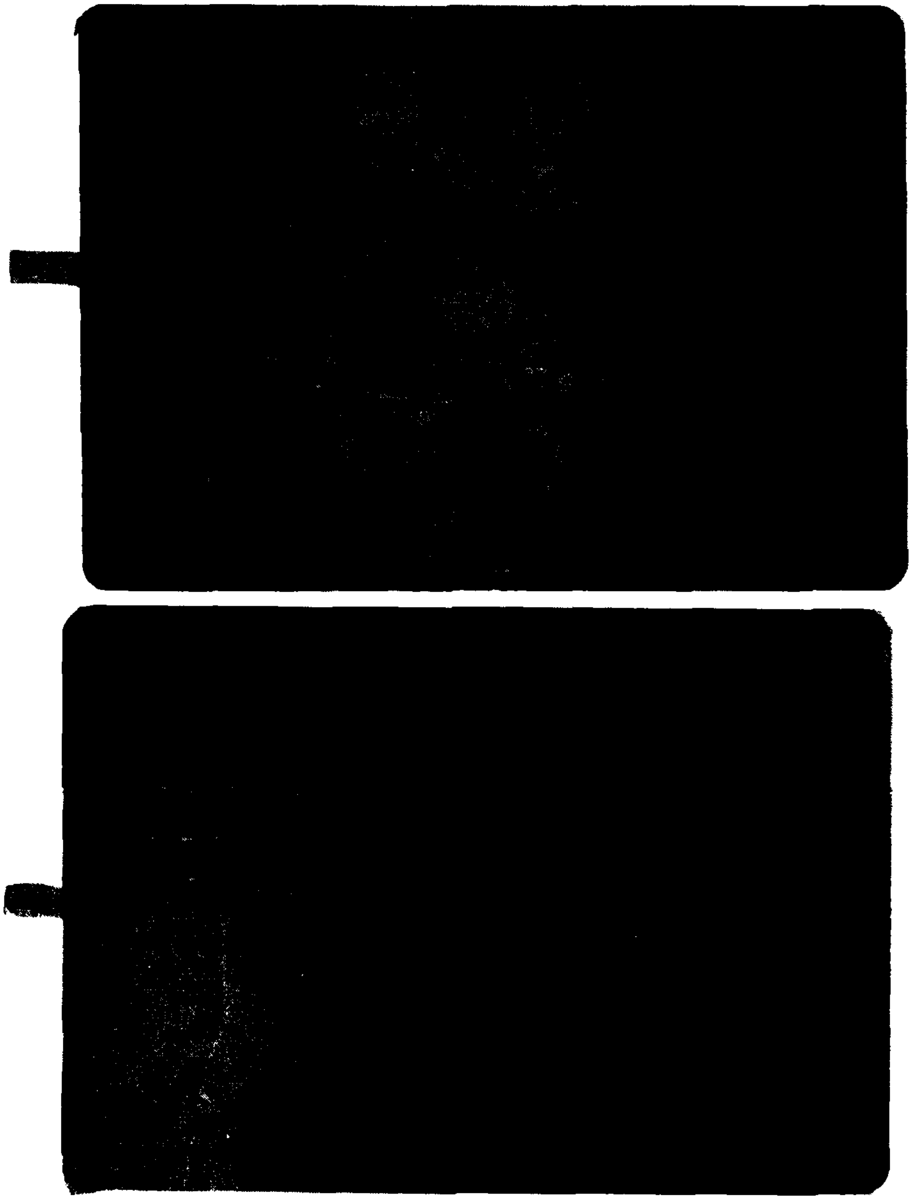


Figure 5-4. (a) Typical foil condition of TCP-impregnated 6 μF capacitor (B-6-C) after 726 discharges at 5.5 kV.

(b) Failure location of same capacitor. Typically, failures were in body (off-edge) and often not in location of foil damage (a, above).

Figure 5-5. Condition of silicone impregnated capacitor sample (C-37) after 6334 discharges at 4.8 kV.

SECTION 6

FULL-SIZE CAPACITOR MANUFACTURE

6.1 STAINLESS CAN FOR SILICONE IMPREGNATED CAPACITORS

The final capacitors to be tested during this program are not themselves destined for spacecraft. However, one group of these capacitors underwent accelerated life testing at 3.9 kV under vacuum with a resistive load which simulates the waveshape of the thruster except for the proportionately higher voltage, current, and $\dot{I}$. A second group of capacitors will undergo life testing in a plasma thruster. Therefore, the requirements of this program called for manufacture of full-scale, 80 μF capacitors in an appropriate steel case virtually identical to that required of a spacecraft in a vacuum environment and throughout the extremes of temperature.

Oil impregnated capacitors manufactured for use on spacecraft must be subjected to extremely stringent screening and quality control procedures to insure the best possible hermetic seal. The basic can is hydroformed from 40 mil thick stainless steel 301 sheet. Special tooling is used to insure dimensional accuracy of each can and minimum material thickness at any point on the can is 25 mils after forming. Cans not meeting dimensional requirements are rejected.

The can is chucked internally and a hole of appropriate diameter is cut in the center of the closed end of the can to accommodate the high voltage center stud bushing. A machined part consisting of the ground ring and mounting flange is vacuum brazed to the closed face of the can. The geometry of this part is such that the ground ring is concentric with the outer circumference to within 0.025 cm (0.01 in.). The center-stud/bushing assembly is then vacuum brazed to the can. Special tooling is used to insure that the center-stud is perpendicular to the front face of the can to within $\pm 0.5^{o}$ and concentric with the ground ring within 0.025 cm (0.01 in.). The resulting assembly is 100% helium leak tested at 1×10^{-9} atm cc/s.

The rear lids are specially machined and matched to each can for a snug fit. The lid is designed to flex without permanent distortion so that volumetric expansion due to temperature excursions can be accommodated. Thus, the capacitors are impregnated at the lowest temperature expected during operation so that the lids are unstressed when the can is sealed off. Internal expansion is taken up by deflection of the lid to insure that excessive pressure does not build up within the can at the maximum operating temperature. The rear lid is welded to the can after the capacitor winding has been installed. Then, after impregnation, the fill plug is soldered in place.

A redundant seal is formed around the center-stud/bushing and bushing/can braze joints by potting these areas with semirigid epoxy. The region around the fill plug is also redundantly sealed in this fashion. A machined metal ring is epoxied over the rear lid weld seam and a machined cap is epoxied over the tip of the center-stud to redundantly seal those areas. The techniques used in redundant sealing of the capacitors have been developed over the years as a result of experimentation using commercially available oil impregnated units. In some cases the "redundant" seals form the primary seals on commercial units. Figure 6-1 shows the output bushing totally filled with the epoxy mixture. For Fairchild Republic tests, the redundant epoxy seal was smaller in diameter than the seal shown.

6.2 TEMPERATURE EFFECTS ON CAN

When the first set of 80 μF capacitors was completed, the two ends of the can appeared to be extended beyond tolerance. This was in part caused by excessive internal pressure which was not taken up by normal expansion of the can bottom

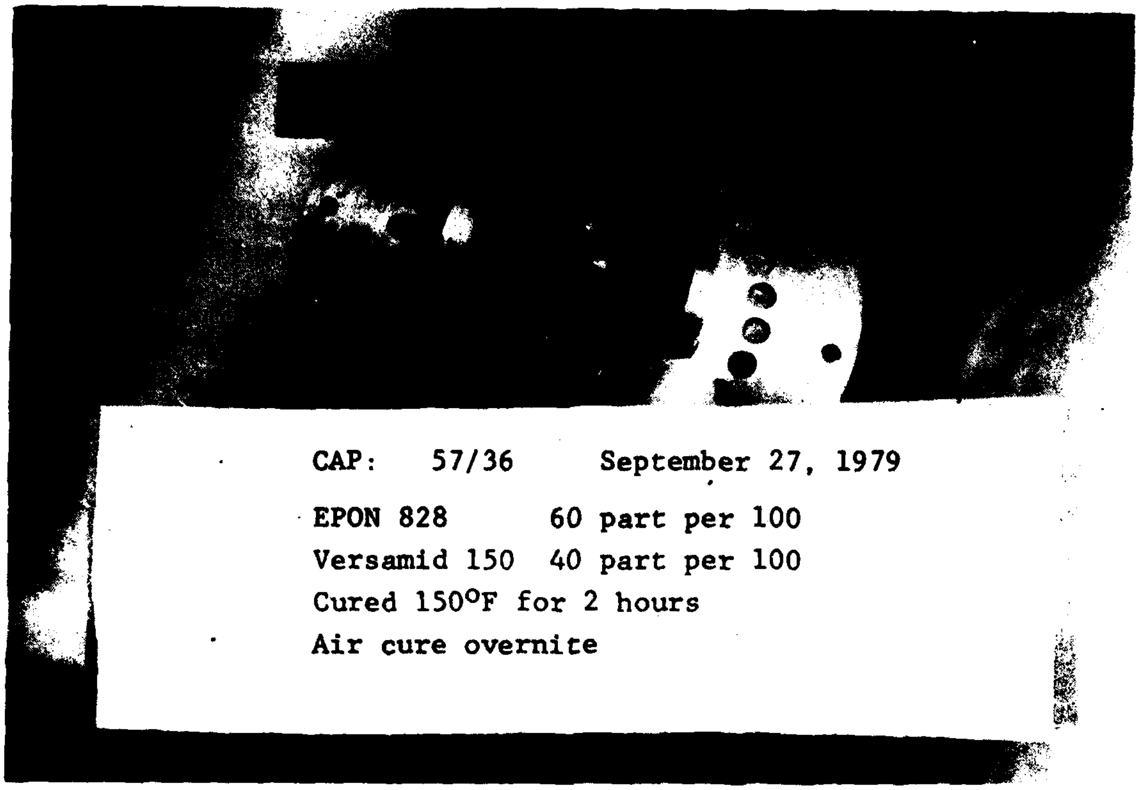


Figure 6-1. Output bushing of 80 μF capacitor showing epoxy redundant seal.

lid. This pressure rise is believed to have been caused by the thermal expansion of the silicone oil impregnant. Table 6-1 shows a comparison of various oils and, as shown, silicone oil has the largest coefficient of thermal expansion.

The design calls for maximum extension only when the capacitor is heated to the peak operating temperature of about 70°C. A careful investigation into the causes of this pressure was conducted. Each can contained 0.2 kg of silicone oil which occupies a volume of about 200 cm^3 (0.92 gm/cm^3). A temperature increase of 10°C causes a volume change of 2 cm^3. Therefore, for each 10°C temperature increase, the flexible lid must take up 1.7 cm^3(0.1 $in.^3$).

Preliminary estimates of volume change due to lid motion indicates a lid excursion of about 0.020-0.025 inches is required to increase can volume by 1.7 cm^3. Estimates of the maximum excursion which the lid can undergo indicates about 0.1 in. can occur. A temperature change of only about 50°C, therefore, can be compensated by lid motion. The production-run capacitor is topped off and sealed at -20°C (according to specification). Therefore, the limit of volume expansion by lid motion was equaled or exceeded when the can reached room temperature.

The above calculations are estimates only. A small error in the above volume calculations (0.5 cm^3) will cause the bushing stud to extend by 0.030 inch beyond its normal position, a value which was reported to Maxwell by FRC.

Possibly this internal pressure contributed to the large number of leaking braze joints experienced during the production of the capacitors. However, it is believed the bushing braze should be capable of withstanding this relatively modest pressure rise.

During this program, capacitors tested at room temperature and above were topped off and sealed at room

Table 6-1. Comparison of volumetric thermal expansion for various capacitor impregnants.

Capacitor Impregnant	Volume Expansion Coefficient (in 10^{-3} $cm^3/cm^3/^oC$)
Silicone oil	1.05
Dielectrol II	0.72
Castor oil	0.66
MIPB	0.80

temperature to maintain low internal pressure. Similarly, the capacitors tested at -20^{o}C were topped off at -25^{o}C. To correct this problem, a modification to the existing lid design is required. A drawing of the capacitor is shown in Figure 6-2.

6.3 CAPACITOR WINDING

6.3.1 Winding Components

The components in each winding are certified by manufacturers to be in conformity with Maxwell's purchase orders. The purchase orders specify capacitor grade foils and films and this designation calls for the highest quality control by the manufacturers. Table 6-2 shows descriptions of the winding components and their weights.

As shown, the components add up to the total weight of 2.1 kg (4.7 lbs). When the can weight of 0.45 kg (1 lb) is included, the total weight of the capacitor is 2.61 kg (5.7 lbs). For an 80 μF, 2.2 kV capacitor with 194 J, the energy density is about 76 J/kg (34 J/lb). This density could have been increased somewhat had a flight capacitor been constructed.

A weight savings of about 5% could have been attained by reducing edge margin. This reduction was not possible during this program because of the necessity to operate at accelerated voltages.

6.3.2 Winding Tension

An important consideration in the winding of K-F polymer capacitors is the winding tension. This was demonstrated during this program by the premature failure of the first group of 80 μF, silicone oil impregnated capacitors which were manufactured for life testing at Maxwell and FRC. A few of those capacitors failed on charge and in all cases, their lives fell short of expectations. In all cases, the failures were at or very near the foil edge margin.

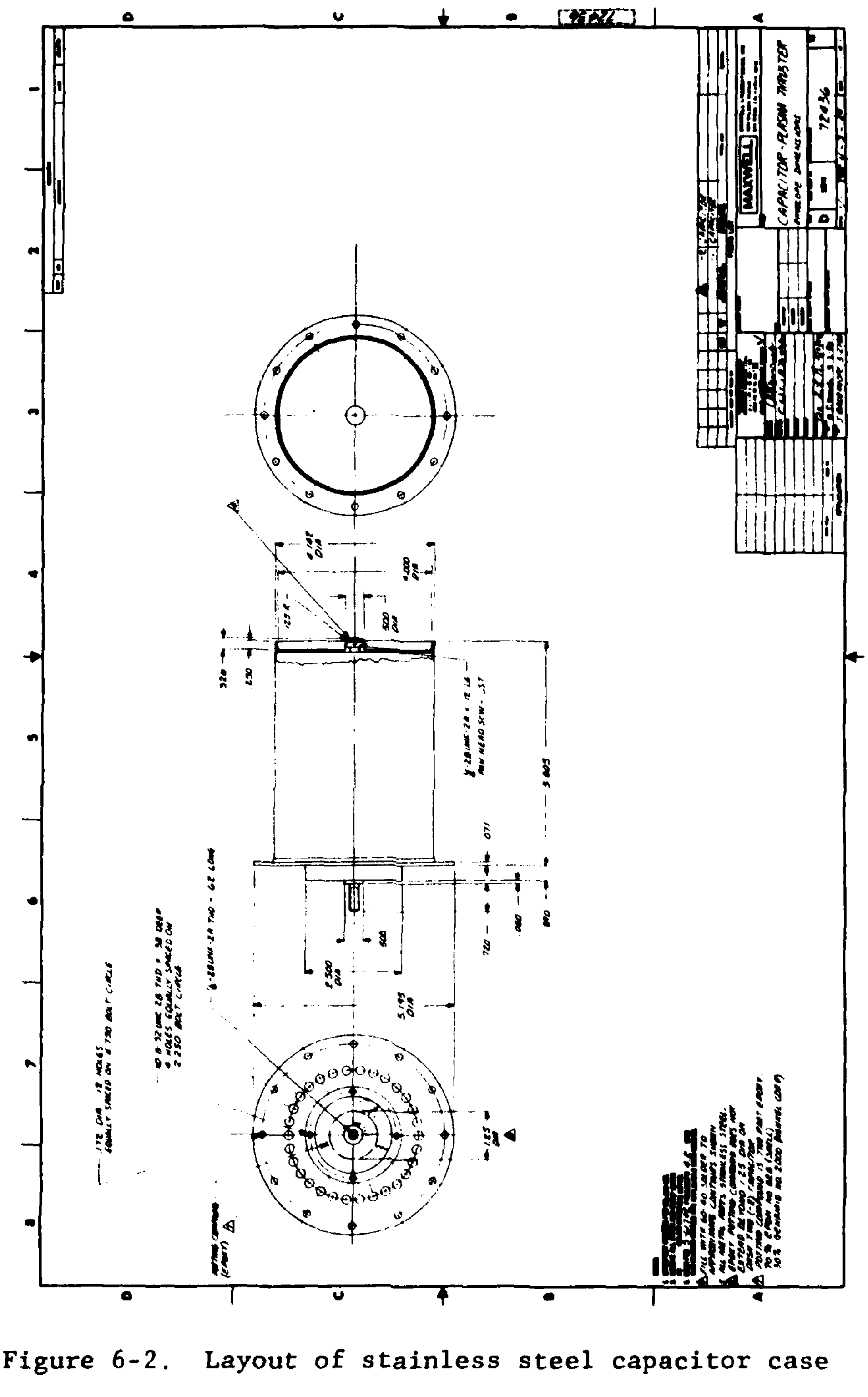


Figure 6-2. Layout of stainless steel capacitor case

Table 6-2. Capacitor Constituents

Material	Manufacturer	Description	Dimensions	Weight/cap.
Foil	Republic Foil	Plain aluminum capacitor foil alloy 1145 (MLI Part 70303)	Width: 12.2 cm (4.81 in.) Thick: 5.8 μ (0.23 mil) Winding length: 107 m (351 ft.)	0.6 kg (1.3 lbs)
Film	Kureha	K-F Polymer (MLI Part 70302)	Width: 12.7 cm (5.0 in.) Thick: 12 μ (0.47 mil) (Double thickness used in winding) Length: 106 m (348 ft.)	1.2 kg (2.6 lbs)
Core		PVC* hollow cylinder filled with polypropylene after winding	Diameter: 2.54 cm (1 in.) Length: 12.7 cm (5 in.) Includes miscellaneous (stud and solder, etc.)	0.09 kg (0.2 lbs)
Impregnant	Dow Corning	DC-200 Silicone fluid		0.2 kg 0.4 lbs)
Capacitor Can	Fairchild Republic	301 Stainless		0.6 kg (1.3 lbs)
Tabs, Solder, Etc.				0.5 kg (0.1 lbs)
			Total	2.7 kg (5.9 lbs)

* For radiation resistant capacitors, PVC is replaced by ceramic.

Careful inspection of the failed windings indicated that excessive winding tension was the probable cause of these edge failures. The K-F polymer appeared to have a sharper than normal crease where the foil ends and the edge margin begins. All capacitors were therefore called back to Maxwell and a new set of windings was successfully fabricated.

In practice, winding tension is regulated by first winding trial samples until a prescribed winding capacitance is obtained. Winding capacitance is measured soon after the windings are made, before any impregnation occurs and before application of high voltage to the winding. This capacitance is called the dry cap. Table 6-3 shows a group of dry caps for serial numbers 50 through 57. Numbers 50-52 and 56-57 were deliberately wound with low tension. Numbers 53-55 were wound with normal tension. As described earlier in this section, this so-called normal tension was determined to result in premature capacitor failure and is therefore considered excessive.

For given setting of the winding machine, the standard deviation of the dry caps is low, $\sigma < 1\%$*, whereas the increment in dry cap between low and normal tension, which is introduced by controlling the winding machine tension, is 10%. A desired value of dry capacitance can be obtained, at will, by minor readjustment of the tension controls.

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* This value is calculated by dividing the standard deviation of the dry caps by the mean dry cap.

Table 6-3. Capacitance measurements on windings before and after application of high voltage.

Serial No.	Dry-Cap μF		Post High-pot μF
52	54.0		66.0
51	54.0		66.0
52	55.0		67.5
53	58.5		67.0
54	59.0	Normal Tension	67.0
55	58.5		67.0
56	55.0		67.0
57	55.0		67.0

SECTION 7

FULL-SIZE (80 μF) CAPACITOR TESTS

7.1 TEST SETUP

The scaled capacitor tests conducted on 6 μF and 30 μF capacitors were conducted with the capacitors immersed in oil to control temperature, as described above. This maintained case temperature below 38°C (100°F) with a discharge frequency of about one discharge per twelve seconds. Depending on the specific objectives of the test, between one and four capacitors were mounted to the multi site switch and tested simultaneously.

In the full scale, 80 μF tests, temperature is actively controlled in order to allow testing at the temperature extremes, as well as at normal room temperature. Discharge tests are conducted, on one capacitor at a time, and it is mounted in a temperature controller. The low inductance strip line which connects the capacitor to the rotating switch passes through the temperature controller, as shown in Figure 7-1.

The case temperature is not held constant during the test. Rather, the nominal test temperature represents the case temperature at the start of the test and as the test proceeds, the case is maintained within a prescribed range. Room temperature tests were conducted in the range from 25°C to 38°C; high temperature tests from 50°C to about 60°C and low temperature tests from -25°C to about -15°C. Temperature is continuously monitored with a strip-chart recorded.

7.2 80 μF SILICONE IMPREGNATED CAPACITORS - MAXWELL TESTS

Based on the scaled tests, the most promising candidate to meet the requirements is the silicone impregnated capacitors. This section discusses the test results on the 80 μF, silicone impregnated capacitors.

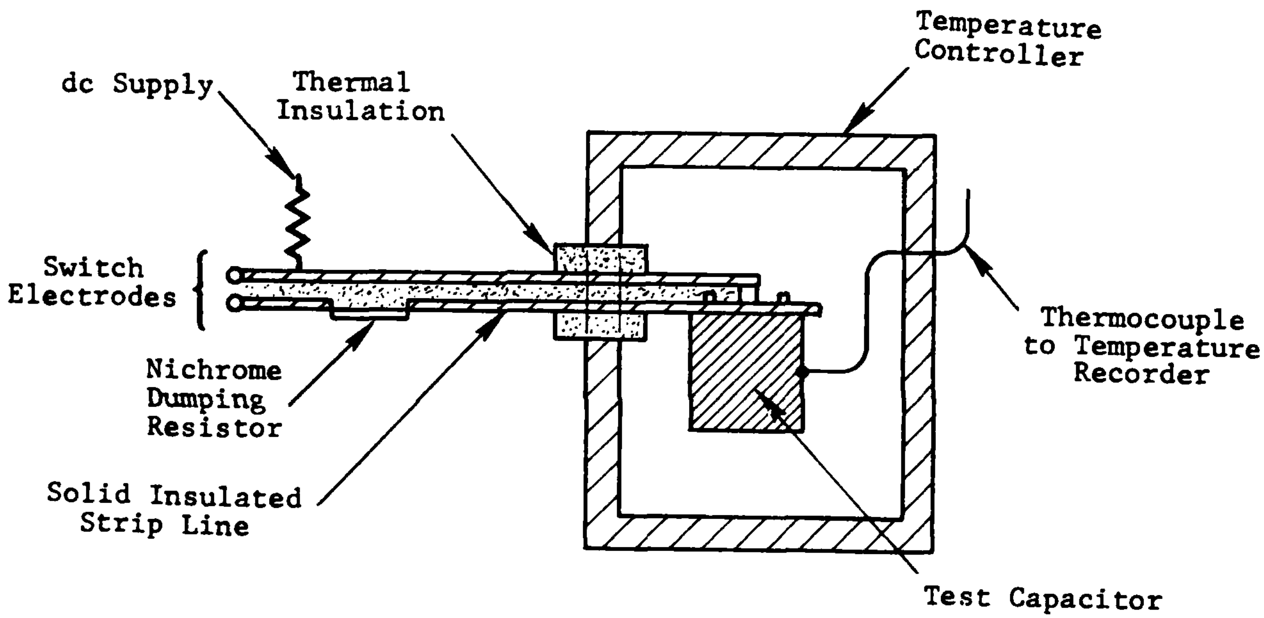

Figure 7-1. Schematic of capacitor in temperature controller.

Life versus Voltage. Discharge life measurements were conducted at a charge voltage of 3.9 kV. To extrapolate to the rated 2.2 kV voltage discharge-life is assumed given by the simple exponential function:

$$L = L_o \left(\frac{V}{V_o}\right)^{-\alpha}$$

where L is life at voltage V, L_o is measured life at voltage V_o and α is an empirical exponent. A more complex expression may be taken from the capacitor literature as providing a better approximation. For example, winding stress may be included in the equation but for purposes of comparing one capacitor life with another, under the same experimental conditions, the formula given above is a good approximation. The data obtained during this program appeared to fit that expression within the tested range up to four decades of life but no data was obtained above that life in order to verify the extrapolation. In the near future a group of four capacitors will be tested in a plasma thruster at FRC and this will shed light on the accuracy of the extrapolation.

To estimate the exponent α, a minimum of two data points is required. For the 80 μF silicone impregnated capacitors tested during this program one data point consists of the mean high pot failure voltage of a group of four capacitors, as shown in Table 7-1. The corresponding life of this group is one since the capacitor fails on charge. The second data point consists of the measured life at a voltage below the high pot value. In this report measured life refers to mean life, $\bar{L}$, characteristic life, or life at 99% reliability, L(0.99). The latter two are obtained from Weibull plots (to be discussed). Therefore, for this report, measured life has three statistical definitions, all of which are based on the

Table 7-1. High pot failure voltage on silicone impregnated capacitors

Number	Failure Voltage, V_{HPF}
97880	5.90
97883	6.60
97882	6.30
97857	6.85

$\bar{V}_{HPF}$ = 6.41 kV ± 0.41 kV.

$\bar{V}_{HPF}$ is the mean high pot failure voltage analysis of measurements on several capacitors at a given voltage.

The results of discharge life experiments on silicone-impregnated capacitors are shown in Table 7-2. Consider the room temperature (25°C) results in which two winding tensions are indicated. (Winding tensions are discussed in Section 6.) The mean life for capacitors with "normal"* tension data is lower than that of capacitors wound with low tension. These points are compared in the Weibull plot of Figure 7-2.

This Weibull plot provides estimates of discharge life as a function of reliability for these 80 μF capacitors. For 1% failure, or reliability of 99%, the discharge life is obtained by extrapolating the plotted line down to the baseline.

Consider the normal tension results. The characteristic life (the life associated with a percentage failure of 63) is 2050 discharges. (This life turned out to be approximately equal to the mean life of 2010 discharges, although usually the mean life was about 20% lower than the characteristic life.) The statistical quantity of significance here is the characteristic life. Mean life is introduced because it is a convenient quantity to calculate and discuss. The life at 99% reliability for room temperature, and normal tension is obtained from the Weibull plot which shows a value of 1600 discharges. This is plotted in Figure 7-3b.

Weibull plots are useful for plotting failures due to high voltage at constant life, i.e. high pot failures, as well as for failures from long life at constant voltage, as

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* In this report, so-called normal tension refers to a winding tension which was used during the scaled tests and which is normally used in production run capacitors.

Table 7-2. Summary of discharge life tests conducted at 3.9 kV charge voltage and at three temperatures.

Nominal Temp.	No.	Tension	Life, $\bar{L}$	$\bar{L}$	σ	$\frac{\sigma}{\bar{L}}$ (%)
≈ 25°C	55	normal	1998			
	53	normal	2081	2010	65	
	54	normal	1952			
	31-5	low	6118	5983	191	3
	31-4	low	5848			
	31-1	low	3747*			
50°C	51	low	887			
	31-6	low	1149	1017	131	13
	31-2	low	1014			
-20°C	31-5	low	12000 (no failure)			
	31-4	low	4601 (bushing failure)			

* Overvoltage during test.

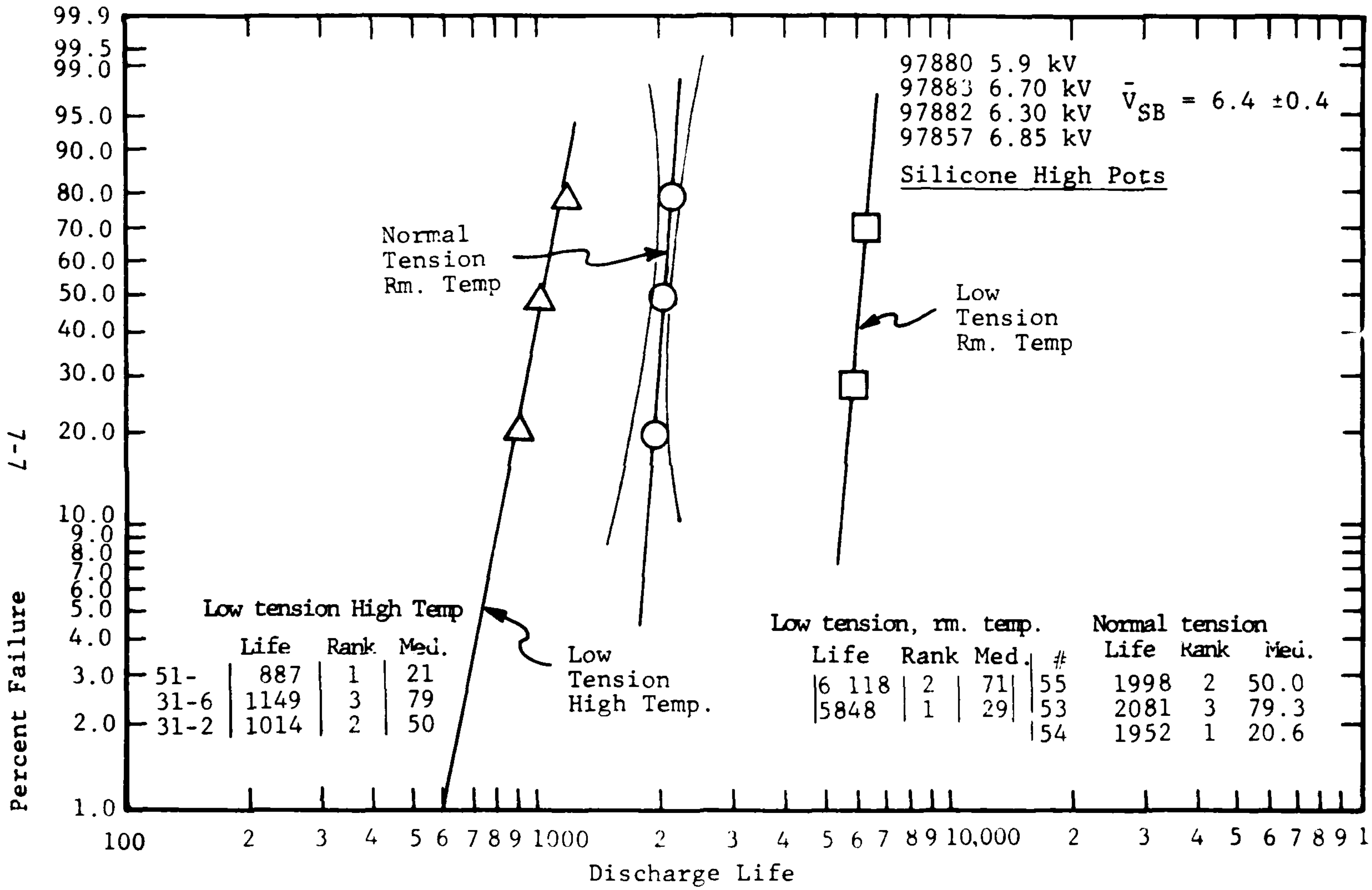


Figure 7-2. Weibull plot of discharge life of silicone oil impregnated tested at 3.9 kV for tests conducted at Maxwell.

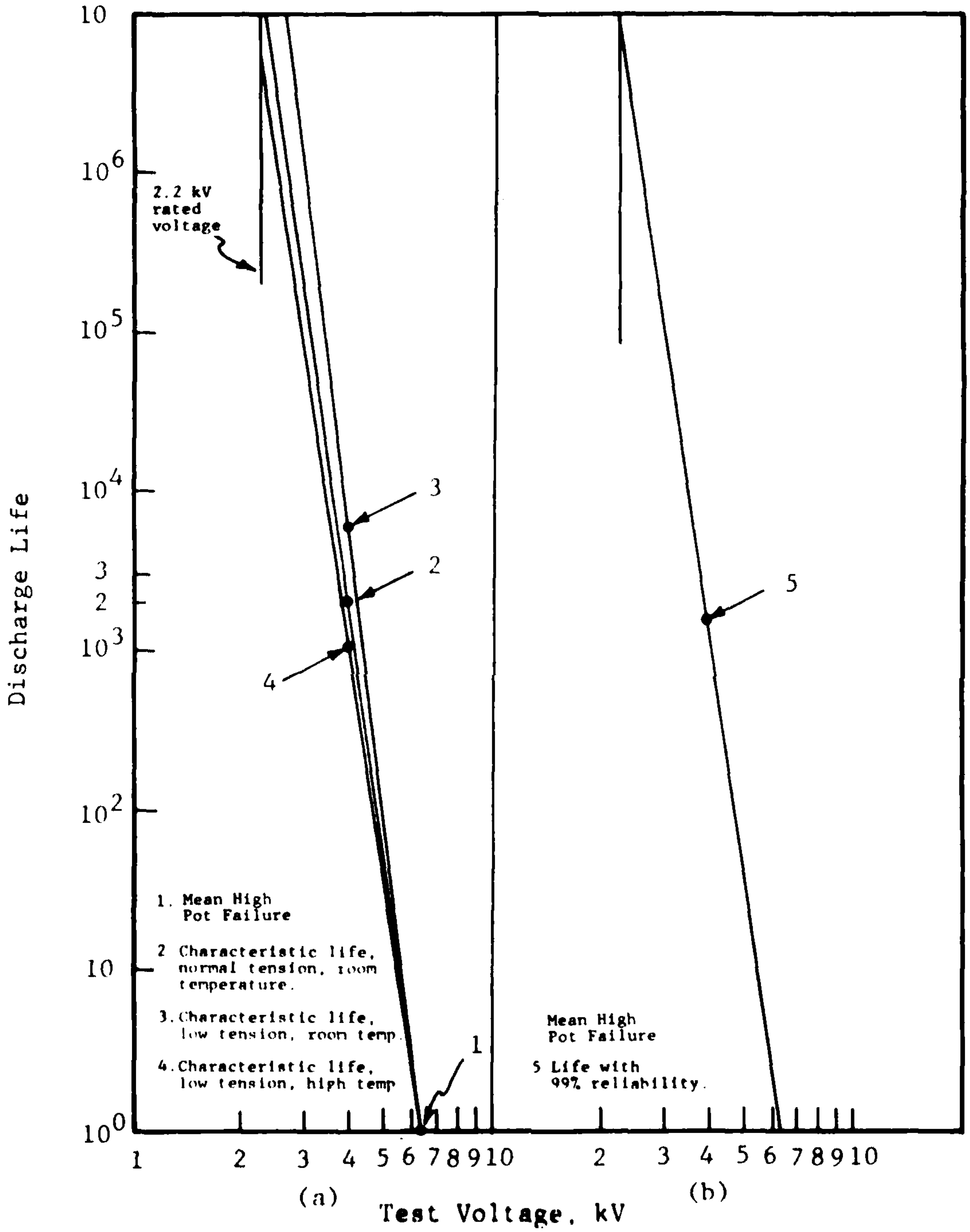


Figure 7-3. Silicone oil-impregnated capacitors - Maxwell test.

discussed above. The latter is the more common application, however. It is important to note that if failures occur with approximately the same life at a given test voltage, or at the same voltage in high pot tests (in which the life is unity), then the three definitions, mean, characteristic, or 99% reliable, all converge to the same value. For example, if all capacitors tested at, say, 3.9 kV fail at the same value of 2000 discharges, the characteristic, mean, and life-with-99% reliability all converge to the value, 2C00. Alternatively, if all high pot voltages are the same, then the mean, characteristic and failure-voltage-with-99% reliability also converge to the same value. This consideration applies to the high pot failures obtained during this program. When they are plotted on a Weibull, the line obtained is nearly vertical (infinite slope). For that reason, the mean high pot voltage is conveniently used on all life versus voltage plots.

Figure 7-3a shows the linear plot on log-log paper of the characteristic life at 3.9 kV and the high pot failure at V_{HPF} = 6.4 kV for normal tension and room temperature. The slope of this line can be calculated from the formula:

$$\alpha = \frac{-\ln(L_2/L_1)}{\ln(V_2/V_1)}$$

where L_2 = 2010 discharges, L_1 = 1 discharge. V_2 = 3.9 kV and V_1 = 6.4 kV.

In that case, α_c - 15.4 where α_c is the slope of the characteristic life curve. This value can be used to calculate the extrapolated characteristic life at the rated 2.2 kV voltage.

$$L_2 = L_1 \left(\frac{V}{V_1}\right)^{-\alpha} = 1 \left(\frac{2.2\ \text{kV}}{6.4\ \text{kV}}\right)^{-15.4} = 1.4 \times 10^7 \text{ discharges.}$$

This calculation is tabulated in Item 1 of the data summary of Table 7-2.

7.3 80 μF, SILICONE IMPREGNATED CAPACITORS UNDER VACUUM, FINISHED TESTS

Test results on the group of four silicone oil impregnated capacitors which were tested under vacuum at Fairchild Republic Corporation are shown in Figure 7-4. These capacitors were tested under the same conditions as those at Maxwell, with the following exceptions:

a. Charging waveform was constant power (charging voltage was proportional to $\tau^{\frac{1}{2}}$ compared to Maxwell charging which was of the form,

$$V \alpha \ (1-\varepsilon^{\frac{-t}{RC}}).$$

b. Capacitor was under vacuum = 10^{-5} torr.

c. Cooling was effected by radiation from the capacitor can to a temperature controlled water jacket. To enhance radiation transfer, FRC capacitors were painted black.

Every effort was made to keep all other aspects of the test the same in both cans. For example, the rep-rate, current waveform and charge voltage (3.9 kV), etc., were the same.

The mean life of FRC capacitors was about 4000 discharges, somewhat smaller than the mean of about 6000 for Maxwell, although clearly within the scatter of the data. Also, the Weibull slopes of the FRC data are significantly smaller than that of the Maxwell data, as can be seen by comparing Figure 7-4 with 7-2. This is important because extrapolations based on FRC data to life with 99% reliability would be smaller than that based on Maxwell data. Extrapolations of FRC data are compared with those of Maxwell in the data summary (Table 7-3).

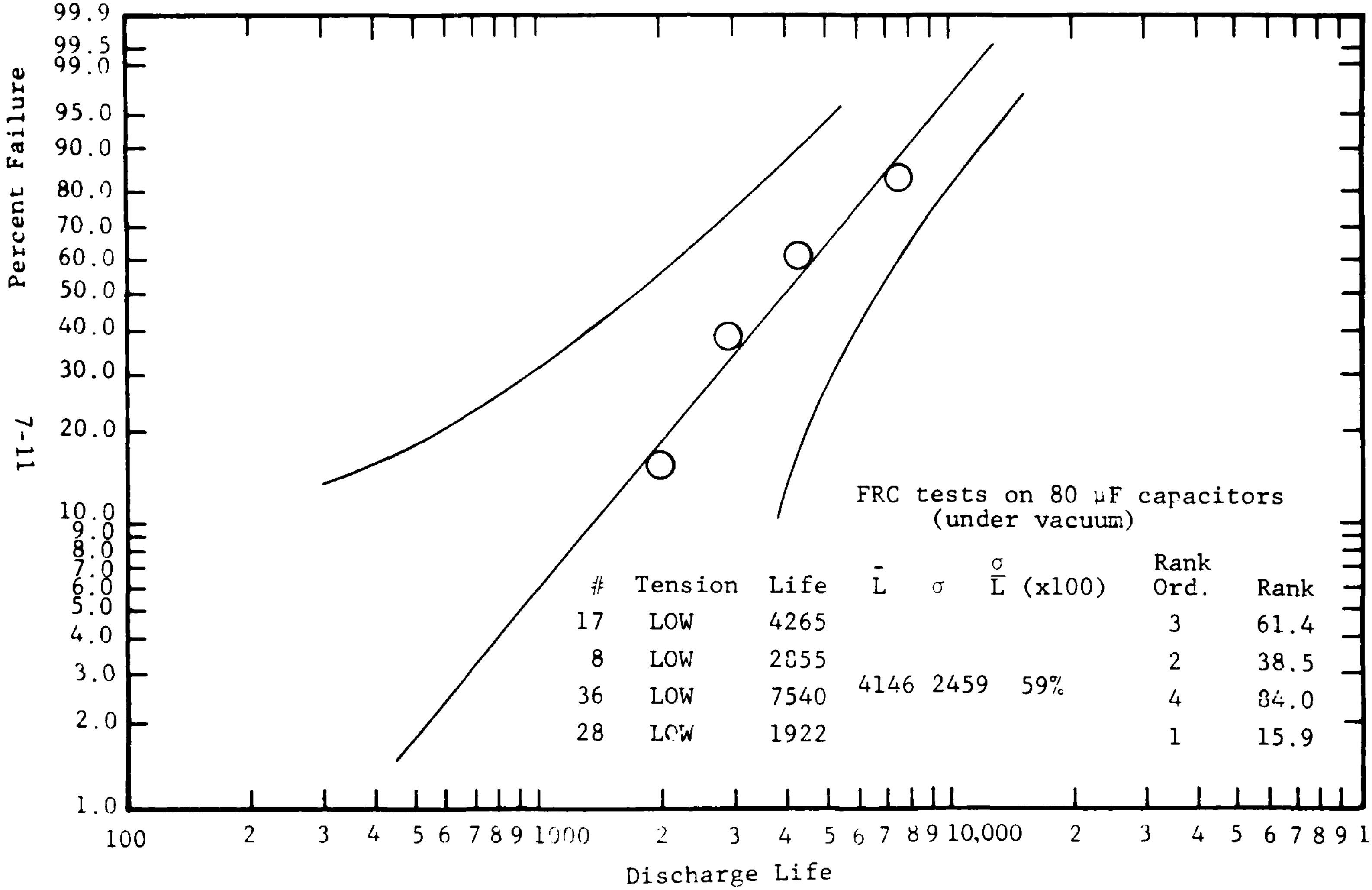


Figure 7-4. 80 µF K-F polymer capacitors impregnated with silicone oil, 3.9 kV. Tests performed at FRC

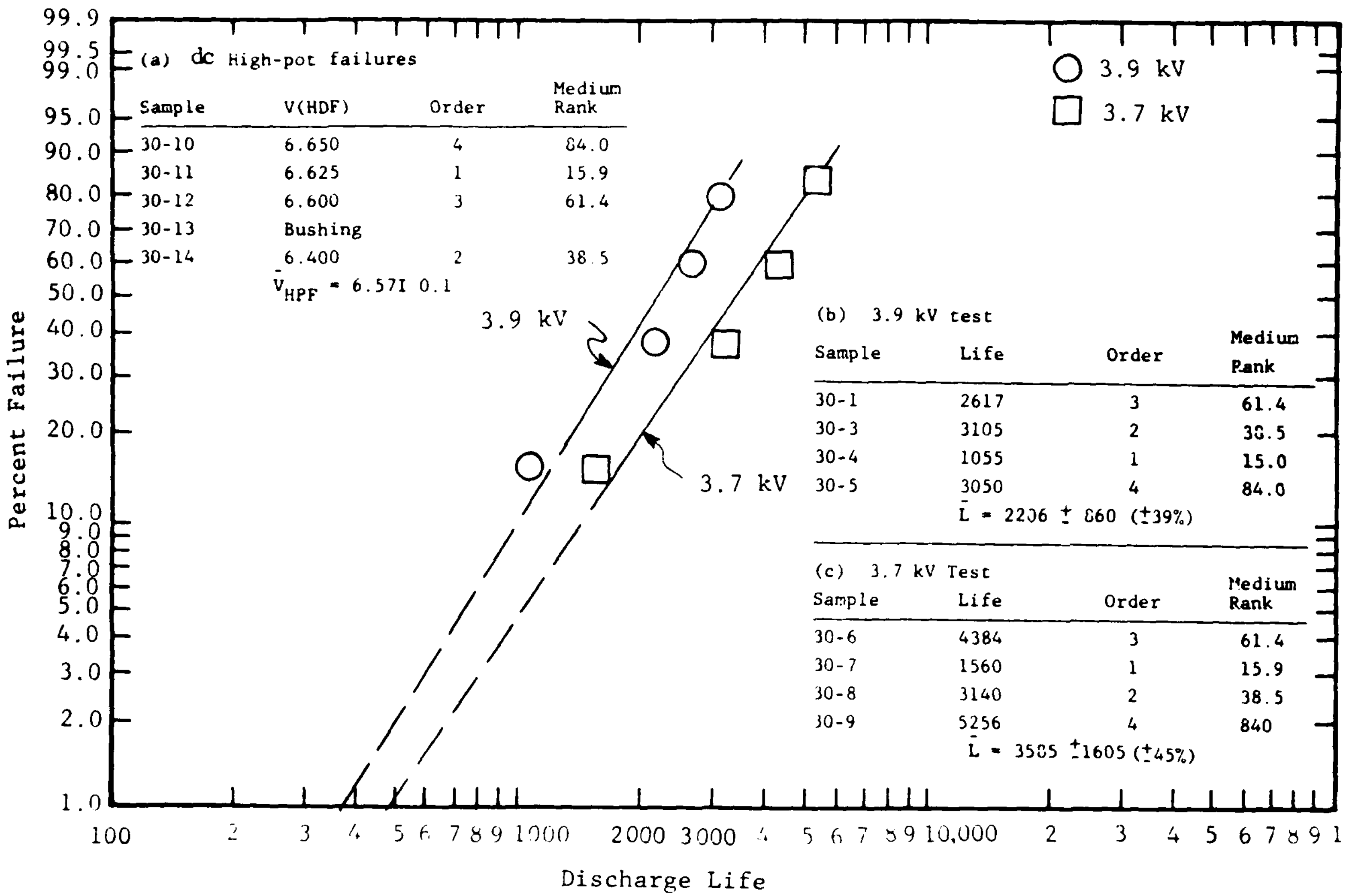
Table 7-3. Summary of discharge-lives of 80 μF K-F polymer capacitors

Capacitor Composition	L(0.37) 3.9 kV	L(0.99) 3.9 kV	α(0.37)	α(0.99)	Extrapolations L(0.37) 2.2 kV	Extrapolations L(0.99) 2.2 kV
I. Silicone Oil Impreg. Test at MLI (3.9 kV)						
Room temp., normal tension	2005	1600	15.4	14.9	1.4×10^7	0.8×10^7
Room temp. low tension	6010	4060	17.6	16.8	1.4×10^8	6.2×10^7
High temp, low tension (3.9 kV)	1007	595	17.6(1)	16.8(1)	2.4×10^7	1.4×10^7
Low temp., low tension (3.9 kV)	$\gtrsim$9000	--	~17.6	--	2.1×10^8	----
II. Silicone Oil Impreg./ vacuum (FRC)						
Room temp (3.9 kV)	4800	360	17.1(2)	11.9(2)	8.5×10^7	3.3×10^5
III. MIPB Impreg. Test at MLI Room temp						
3.9 kV test	2500	360	15.0(3)	11.3(3)	1.3×10^7	2.3×10^5
3.7 kV test	3900	470	14.4	10.7	0.7×10^7	1.2×10^5

(1) Slopes at high and low temperature assumed equal to that of room temperature.

(2) Mean high-pot failure of 6.40 kV is assumed for FRC capacitors (as for Maxwell)

(3) Mean high-pot failure for MIPB impregnated capacitor is 6.57 kV



(a) dc High-pot failures

Sample	V(HDF)	Order	Medium Rank
30-10	6.650	4	84.0
30-11	6.625	1	15.9
30-12	6.600	3	61.4
30-13	Bushing		
30-14	6.400	2	38.5

$\bar{V}_{HPF}$ = 6.57I 0.1

(b) 3.9 kV test

Sample	Life	Order	Medium Rank
30-1	2617	3	61.4
30-3	3105	2	38.5
30-4	1055	1	15.0
30-5	3050	4	84.0

$\bar{L}$ = 2206 ± 860 (±39%)

(c) 3.7 kV Test

Sample	Life	Order	Medium Rank
30-6	4384	3	61.4
30-7	1560	1	15.9
30-8	3140	2	38.5
30-9	5256	4	840

$\bar{L}$ = 3585 ±1605 (±45%)

Figure 7-5. Weibull plot of 80 μF MIPB-impregnated K-F polymer capacitors. Maxwell tests at 3.9 kV and 3.7 kV.

7.4 MIPB IMPREGNATED CAPACITORS (MAXWELL)

Weibull plots of the MIPB discharge lives are shown in Figure 7-5. By comparing the MIPB failures with that of silicone oil, it is apparent the silicone oil is superior. The silicone oil capacitors and the MIPB impregnated capacitors were tested under the same conditions with the exception that the MIPB capacitors were enclosed in conventional steel cases, whereas the silicone capacitors were encased in the special stainless steel cases. Figure 7-6 shows the extrapolations of MIPB life to the rated voltage of 2.2 kV.

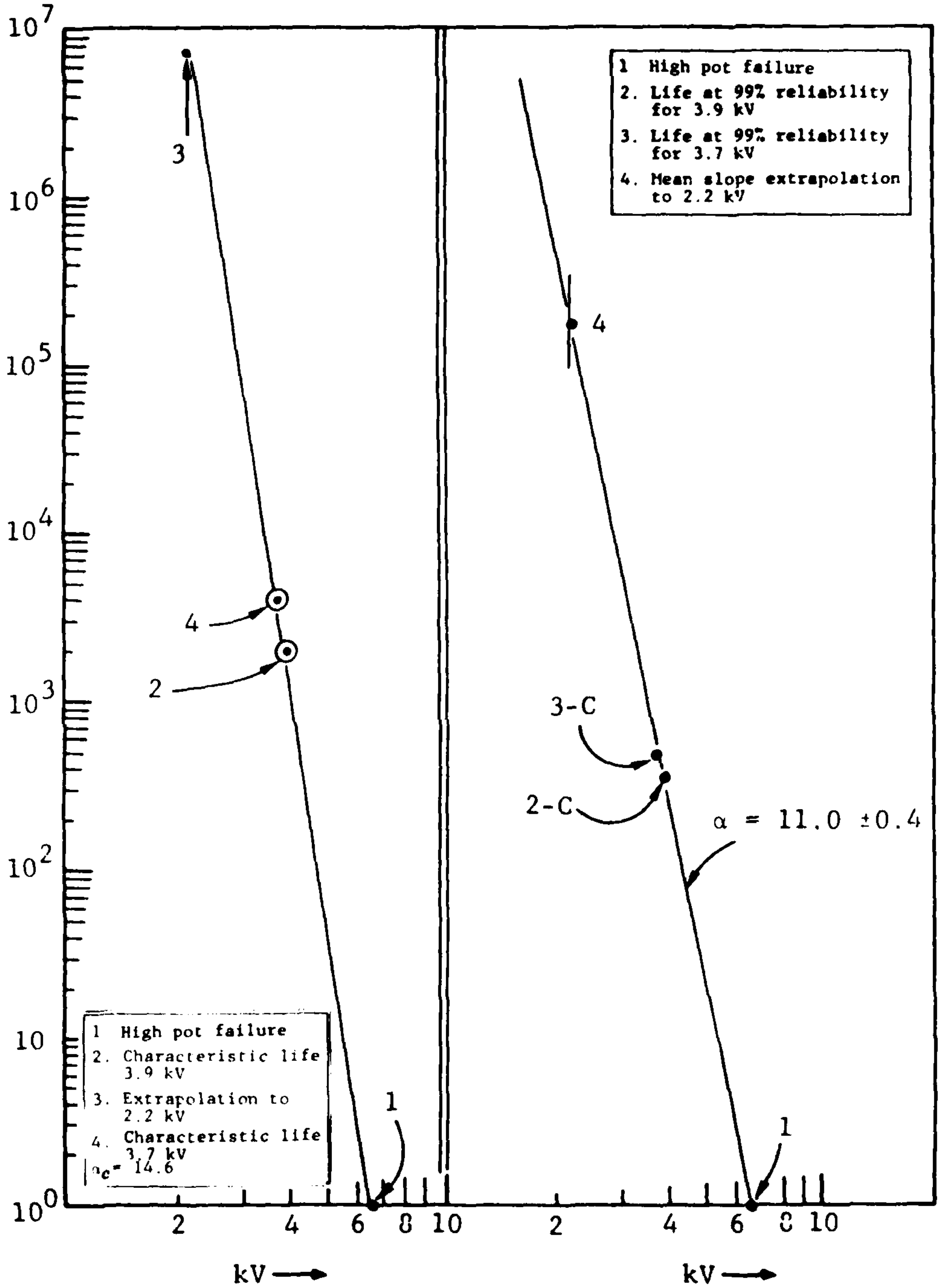


Figure 7-6. Extrapolations of discharge-life for MIPB impregnant, 80 μF K-F polymer capacitors.

SECTION 8

CONCLUSIONS

Throughout the program, capacitors failed within the body of the capacitor, in contrast to failures which occur at foil edges. Generally, the capacitor industry considers the appropriate location of failures to be the foil edge because that is the most highly stressed region of the winding. When the failure occurs off-edge, i.e. in the bulk of the material, it suggests a failure mechanism occurred which is distinct from normal wear-out. Often, such a mechanism is not as predictable as edge failures. For example, inclusions of foreign particle pin holes or material fatigue may cause such bulk failures. Normally, when foil edge failures occur, neighboring foil edges are burned slightly, indicating a gradual wear-out of the edge.

In the case of these K-F polymer capacitors, edge failure was extremely rare; only when windings with higher than optimum tension were fabricated, did the failure occur at or near the edge. When the winding tension was reduced, the failure mode reverted to that of body failure. In summary, doubts persist as to whether or not the full capability of this material is being utilized.

Based on the limited data on final capacitors obtained during this program, the silicone capacitors are capable of meeting the program goals provided the operation temperature does not exceed about 38°C. In the "low" and "room" temperature experiments, the life-with-99% reliability appears to be well into the 10^7 range. Table 7-3 showed a data summary which includes all 80 μF tests. As shown, MIPB appears less attractive than silicone oil as a K-F polymer capacitor impregnant. This is unfortunate since MIPB has known resistance to radiation.

It is hoped a future program will assess the capability of silicone impregnated K-F polymer capacitors to withstand radiation bombardment.

This program met the objective of demonstrating the feasibility of constructing a long-life, all-film capacitor employing K-F polymer. An effort was made to utilize the data available to predict the life at rated charge voltage of 2.2 kV. In a future program, it is hoped a larger number of capacitors will be tested in order to provide a statistical basis for these extrapolations.

APPENDIX A

LIST OF LIQUIDS WITH DIELECTRIC CONSTANT GREATER THAN 5

(1)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
1	Dichloromethane (methylene chloride)	CH_2Cl_2	30°	8.649	1		0.43 lp @20°C	Surf. tens. 26.52 dynes/cm MP -97°C BP 4[illegible].1°C @ 20°C poisonous fumes
2	1, 1, 1-Trichloroethane	$C_2H_3Cl_3$	20°	7.228	1			BP 74.2°C Solvent Mp-33°C BP 74°C
3	2-Propyn-1-01 (Propargyl alcohol)	C_3H_4O	-40° 20°	34 21.6	1			MP -17°C BP 114°C Corrosion inhibitor stabilizer
4	2-Propyn-1-01 (Allyl Alcohol)	C_3H_6O	-130° 20°	63 20.8	1			(see #65) MP -50°C BP 96°C flash point 70°F
5	N, N-Dimethyl-formaldehyde	C_3H_2ON	20°	38.7	1			(high vap. pres.) MP -61°C BP 153°C
6	Tetrahydroturan (Methyl Ethyl Notor)	C_4H_8O	30° 50°	7.261 6.272	1		0.417 CP @ 21.3°C	(high vap. pres.) fr-65°C br 153°C
7	Ethylacetate	$C_4H_8O_2$	30° 50°	5.984 5.422	1		0.582CP @ 0°C	Surf. tens. 23.9 dynes/cm @ 20°C. flammable BP 71.1°C flashpoint 26°C
8	N-N-Dimethyl-acetamide	C_4H_8ON	20°	40.2	1			MP -20°C BP 161°C flash point 151°F
9	N-N-Dimethyl-proponamide	$C_5H_{11}ON$	20°	34.6	1			
10	N-N-Diethyl-formaldehyde	$C_5H_{11}ON$	20°	29.6	1			
11	O-Dichlorobenzene	$C_6H_4Cl_2$	20°	10.57	1			FP -198 heat tr BP 178°C
12	Chlorobenzene	C_6H_5Cl	30° 50°	5.552 5.216	1		0.90 CP @ 15°C	Surf. Tens. 33.56 dynes/cm @ 20°C FP - 45°C BP 131.6°C
	"	"	-45°	7.16	2			

(2)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
13	N-N-Dimethyl butyricacidamide	$C_6H_{13}ON$	20°	29.7	1			
14	N-N-Diethylacetamide	$C_6H_{13}ON$	20°	32.1	1			
15	Benzylchloride	C_7H_7Cl	20° 40°	7.095 6.618	1			mp -43°C bp 179°C corrosive liquid
16	N-N-Dimethylvalericacidamide	$C_7H_{15}ON$	20°	26.4	1			
17	N-N-Di-n-propyl formaldehyde	$C_7H_{15}ON$	20°	23.5	1			
18	N-N-Dimethylcaproicacidamide	$C_8H_{17}ON$	20°	22.7	1			
19	N-N-Di-n-propylacetamide	$C_8H_{17}ON$	20°	24.5	1			
20	Dimethyl heptaanoicacidamide	$C_9H_{19}ON$	20°	20	1			
21	N-N-Di-n-butylformamide	$C_9H_{19}ON$	20°	18.4	1			
22	Dimethyl octanoicacidamide	$C_{10}H_{21}ON$	20°	17.4	1			
23	N-N-Di-n-butylacetamide	$C_{10}H_{21}ON$	20°	19.1	1			
24	N-N-Dimethyl nonanoicacidamide	$C_{11}H_{23}ON$	20°	15.8	1			

(3)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
25	N,-N-Dimethyldeca-noicacidamide	$C_{12}H_{25}ON$	20°	13.8	1			
26	N,-N-Di-n-amyl-acalamide	$C_{12}H_{25}ON$	20°	15.8	1			
27	N,N-Di-n-octyl-acetomide	$C_{18}H_{37}ON$	20°	11.5	1			
28	1,1,2,2-Tetra bromo-ethane	$C_2H_2Br_4$	30° 60	6.72 5.77	2			MP -1°C BP 239°C
29	1,1-Dichloro-1-nitro ethane	$C_2H_3O_2Cl_2N$	30° 60°	16.3 14.15	2			
30	Succinonitrile (ethylene cyanide)	$C_4H_4N_2$	50°	56.4	2			mp 57°C bp 265.7°C
31	2-Chloro-2-methyl propane (tert-Butyl chloride)	C_4H_9Cl	-25° -40°	12.74 8.75	2			mp -27.1°C bp 50.7°C
32	Bromobenzene	C_6H_5Br	-30° 50°	6.24 5.04	2		1.196 CP @ 15°C	Surf. Tens. 36.5 dynes/cm @ 20°C FP -30.5°C BP 156°C
33	Iodobenzene (pienyl iodide)	C_6H_5I	-30° 50	5.12 11.32	2		1.74 CP @ 15°C	mp-31.4°C bp 189°C
34	Nitrobenzene	$C_6H_5O_2N$	6° 60°	38.6 28.4	2		2.91 CP @ 29.5°C	Surf. Tens. 43.9 dyn/cm @ 20°C MP 5.7°C poisonous BP 210.8°C
35	2-Methyl-2,4,-penta-nediol (Hexylene Glycol)	$C_6H_{14}O_2$	-70° 60°	47.8 20.1	2			Penetrant for textiles miscible with water BP 198°C Flashpoint 230°F
36	Dipropleneglycol	$C_8H_{18}O_2$	-60° 60°	34.5 15.66	2		1.07 poise @ 20°C	solvent bp 231.8°C

(4)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
37	2, Ethyl-1, 3-hexanediol	$C_8H_{18}O_2$	-40° 60°	25.00 15.24	2			fp < -40°C bp 244.2°C
38	Quinoline (levhol)	C_9H_7N	-15° 50°	10.45 8.39	2			Surf. Tens. 45.0 dyne/cm. @ 20°C MP -15°C BP 238°C
39	"Econol" (G.E. Proprietary)	Phthalate Ester base	25°C 75°C	5.2 4.6	3			Pour point - 45°C U.S. Patent 3,754,173
40	Niax polyol 10 ring 130	?	24° 42° 61°	8.80 7.94 7.81	4			
41	Niax polyol W137 D 408	?	74°	9.85 to 7.96	4			9.85 at 1 kHz 7.96 at 100 kHz
42	Isocyanate SF-52	?	28° 77	14.7 11.9	4			
43	"Stypol" 16B monomer	?		7.16	5			7.16 @ 10^4 Hz, tan δ = 79 x 10^{-4} 3.02 @8.6 x 10^5 Hz; tan = 420 x 10^{-4}
44	Aerochlor 1254 with 0.5% anthraquinone	?		5.5 max	6			graphs of ϵ vs. T " " tan δ vs. T
45	86% Aerochlor 1254 14% TCB	?		6.08 max	6			" " "
46	75% Aerochlor 1254 25% TCB w/ anthraquinone	?		6.13 max	6			" "
47	Aerochlor 1232	?	25°	5.88 @ 10^6 Hz	7			tables of ϵ vs. f " " tan δ vs. f
48	Aerochlor 1242	?	25°	5.89 @ 10^6 Hz	7			" " "

(5)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
49	Aerochlor 1248	?	25°	5.57 @ 10^6 Hz	7			Tables of ϵ vs f " " tan δ vs f
50	Water	H_2O	1.5° 25° 75°	87 78.2 61.5	7			Tables of ϵ vs. T " " tan δ vs f Surface tension 73.01 dyne/cm @ 18°C
51	Methy alcohol (methanol)	CH_4O (CH_3OH)	25°	31 @ 10^6 Hz	7		1.98 CP @ -44.5°C	mp - 97.8°C bp 64.5°C Surf. tens. 22.6 dyn/cm @ 20° c.
52	Ethyl alcohol (ethanol)	C_2H_6O (C_2H_5OH)	25°	24.5 @ 10^6 Hz	7		3.84 CP @ -32°C 1.77 cP @ 0°C	mp - 117°C bp 78°C flash pt 14°C surface tension 22.8 dyn/cm @ 20°C
53	N-Propyl alcohol (1-propanol)	C_3H_8O	25°	17.4 @ 10^6 Hz	7	C_p = 34.74 μ = 1.66@ 24°C	3.88 CP @ 0°C	mp -127°C flashpoint 59° F bp 97.2°C surface tension 23.78 dyn/cm @ 20°C
54	n-butyl alcohol	$C_4H_{10}O$	25°	17.4 @ 10^6 Hz	7	C_p = 51.51 μ = 1.68	14.7 CP @ -30°C 5.18 CP @ 0°	fp - 89°C flashpoint 100° F bp 117.7°C surface tension 24.6 dyne/cm @ 20°C
55	Ethylene glycol	$C_2H_6O_2$	25°	6.7 @ 10^6 Hz	7		19.9 CP @ 20°C	" solvent mp - 12°C bp 197.2°C
56	Butyraldehyde		25°	6.7 @ 10^6 Hz	7		0.0043 p @ 20°	" FP-99°C BP 75.7°C
57	Dichloropentane #14	$C_5H_{10}Cl_2$	25°	8.05 @ 10^6 Hz	7			" solvent surface tension 31.8 dyn/cm @25°C
58	Nitrobenzene	$C_6H_5NO_2$	25°	35.6 @ 10^6 Hz	7			See No. 34
59	B_1 chloroethel-2, 5-dichlorobenzene		24°					
60	Aniline	$C_6H_5NH_2$	20°	7.21	8		13.8 CP @ -6° 4.4 CP@20°	surf. tens. 42.9 dyn/cm @ 20°C mp -6.2°C bp 184.4°C poisonous

(6)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data	
61	Acetone (dimethyl ketone)	$(CH_3)_2CO$	20°	21.3	8	C_p = 30.87 μ = 2.72	0.695CP@ -42.5°C	Surf. Tens. 23.7 dyn/cm @ 20°C solvent	mp-94.3°C bp 56.1°C
62	0-Nitrotoluene	$C_6H_4CH_3NO_2$	20°	27.42	8		3.83 CP@ 0°C		mp-9.55°C bp 222.3°C
63	Formic Acid	CH_2O_2	2° 18.5°	19 47.9	8		1.635 C.P. @24.16°C	corrosive liquid	mp 8.3°C bp 100.8°C
64	Methyl Ethyl Ketone	C_4H_8O	17°	18.1	8		0.417 CP @ 21.3°C	Surf. Tens. 24.6 dyn/cm @ 20°C	mp -86.4°C bp 79.6°C
65	Allyl Alcohol (2-Propen-1-01)	C_3H_6O	15°	21.6	8		1.283 CP @22.8°C	Surf. Tens. 25.8 dyn/cm @20°C poisonous	mp -129°C bp 96.9°C flash pt. 70°F
66	Formamide (methanamide)	CH_0NO	20°C	> 84	8		3.359CP @ 25°C	Solvent	mp 2.5°C bp 200°C
67	Nitromethane	CH_3NO_2	0° 20°	45 39	8		0.619 CP @ 25°C	Surf. Tens. 36.82 dyn/cm @ 20°C solvent	fp -29°C bp 101°C
68	Chloral	C_2HCl_3O	-20° 0° 20°	6.5 5.6 4.9	8		0.126CP @ 25° 1.01CP@40°	Surf. Tens. 25.34 dyn/cm @20°C Hazardous liquid and vapor	mp -57.5°C bp 97.7°C
69	Tetrachloroethane (acetylene tetrachloride)	$C_2H_2Cl_4$	25° 20°	7.8 8.2	8		1.637CP @ 25°C	Surf. Tens. 31.74 dyn/cm hazardous vapor	fp -43°C bp 146.5°C
70	Acetonitrile (methyl cyanide)	C_2H_3N	0° 20° 81.6pp	42 38.8 26.2	8	C_p = 21.3 μ = 3.37	0.36CP @25°C	Surf. Tens. 29.3 dyn/cm @ 20°C poisonous	mp -111°C bp 82°C
71	1,1-Dichloroethane (Ethylidene Chloride)	$C_2H_4Cl_2$	0° 20° 50°	11.6 10.4 9.4	8	C_p = 31.18 μ = 1.95	0.493CP @ 19.3°	Surf. Tens. 23.4 dyn/cm @ 20°C	fp -98°C bp 57°C
72	Acetaldehyde	C_2H_4	10° 20°	22.2 21.6	8	C_p = 15.0	0.223CP @19.17°	Surf. Tens. 21.2 dyn/cm @20°C	mp_1 - 123°C bp 20.2°C

(7)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
73	Ethylene Oxide	C_2H_4O	-1°	13.9	8		0.29CP @9.3°C	Surf. Tens. 24.3 dyn/cm @20°C; mp -111.3°C bp 10.7°C
74	Methyl Formate	$C_2H_4O_2$	0° 20°	9.2 8.2	8		0.3467CP @20.15°C	Surf. Tens. 25.08 dyn/cm @ 20°C; mp -99.8°C bp 31.8°C
75	Ethyl Bromide (Bromoethane)	C_2H_5Br	20° 1.4°	9.4 10.5	8	$C_p = 0.2088 + 4.88x10^{-4}t$	1.698CP @ 20.6°C	Surf. Tens. 24.15 dyn/cm @ 20°C surf. tension 25.48 dyn/cm @10°C; mp -118°C bp 38.4°C
76	Ethyl Iodide (Iodoethane)	C_2H_5I	20°	7.4	8		0.5782 CP @20.8°C	Surf. Tens. 29.4 dyn/cm @ 20°C; mp -108°C bp 72°C
77	Glycol (Ethylene Glycol)	$C_2H_6O_2$	0° 20° 50°	47.0 41.2 35.6	8		17.4 CP @ 25°	(see #55)
78	Dimethyl Sulfate	$C_2H_6O_4S$	0° 20°	58.9 55.0	8		2.73 CP @ 0°C	Surf. Tens. 40.12 dyn/cm @20°C corrosive liquid; mp -26.8°C bp 188°C
79	Dimethyl Sulfide	C_2H_6S	20°	6.3	8		0.29 CP @ 20°C	mp - 83.2 bp 37.5°C
80	Ethylmercaptan	C_2H_6S	20°	8.0	8		0.21 CP @ 25°C	Surf. Tens. 22.5 dyn/cm @20°C; mp -121°C bp 36°C
81	Ethylamine (aminoethane)	C_2H_7N	21°	6.3	8		0.437 CP @ -33.5°C	Surf. Tens. 20.4 dyn/cm strong alkaline reaction; fp -81.2°C bp 14.5°C
82	Ethylene diamine	$C_2H_8N_2$	18°	16.0	8		1.54 CP @ 25°C	strong base; mp 8.5°C bp 116°C
83	Malonic nitrile (cyano acetic acid)	$C_3H_2N_2$	36°	47.2	8		2.85 CP @ 32.7°C	mp = 66°C bp = 108°C Soluble in water, alcohol, chloroform.
84	Epichlorohydrin	C_3H_5ClO	0° 20°	25.7 22.9	8	$\mu = 1.8$	1.03 CP @ 25°C	unstable; fp -58°C bp 115°C

(8)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
85	Propionitrile (ethyl cyanide)	C_3H_5N	0° 20° 50°	31.6 27.7 24.6	8	C_p = 27.8 μ - 3.56	0.54 CP @ 0°	Surf. tens. 27.2 dyn/cm @ 20°C. poisonous; mp -103.5°C, bp 97°C
86	Ethyl thiocyanate (Ethyl sulfocyarate)	C_3H_5NS	0° 20°	35.3 29.6	8		1.10 CP @ 0°	Surf. tens. 36.2 dyn/cm @ 20°C. bp 146°C
	Allyl Alcohol	C_3H_6O	15° 21°	21.6 21.0	8		1.28 CP @ 22.8°C	(see #65)
88	Propionaldehyde	C_3H_6O	15°	14.4	8		0.467 CP @ 0°C	bp 48.8°C, mp. -81°C
89	Acetone	C_3H_6O	0° 50°	23.2 18.7	8		0.3258 CP @ 19.0°C	(see #61)
90	Ethyl Formate (formic ether)	$C_3H_6O_2$	14°	91	8	C_p = 35.37 μ = 1.94	0.391 CP @ 22.59°C	Surf. Tens. 23.6 dyn/cm @ 20°C; mp -80.5°C, bp 54.3°C; extremely flammable, flashpoint 14°F
91	Methyl Acetate	$C_3H_6O_2$	20°	7.3	8	C_p = 37.19 μ = 1.75	0.3706 CP @ 20°C	Surf. tens. 24.6 dyn/cm @ 20°C. mp -98°C, bp 54°C
92	Lactic Acid	$C_3H_6O_3$	19°	23	8		40.5 CP @ 25°	mp 18°C, bp 122°C
93	Propyl Bromide (1-bromo propane)	C_3H_7Br	20°	7.2	8	C_p = 0.2586+ $5.25x10^{-4}$ t μ = 1.93	0.52 CP @ 19.17°C	Surf. Tens. 19.65 dyn/cm @ 20°C; mp -110°C, bp 71°C
94	Propyl Chloride (1-chloropropane)	C_3H_7Cl	20°	7.7 @ $5x10^6$ Hz	8	m C_p = 0.382+ $7.95x10^{-4}$ t μ = 1.97	0.349 CP @ 20.7°C	Surf. Tens. 18.2 dyn/cm @ 20°C; mp -122°C, bp 46°C
95	Propyl Alcohol	C_3H_8O	-50° 0° 20°	32.0 24.5 21.8	8		2.555 CP @ 15°C	Surf. Tens. mp -127°C, bp 97.2°C
96	Isopropyl Alcohol	C_3H_8O	15°	19.8	8	C_p = 35.79 @ 19.7 μ = 1.68	2.81 CP @ 14.4°	Surf. Tens. 21.7 dyn/cm @ 20°C; mp -87.9°C, bp 82.4°C, flashpoint 53°F

(9)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
97	Isopropylamine	C_3H_9N	20°	5.5	8		0.35 CP @ 25°C	Strong base; fp -95.2°C; bp 32.4°C
98	Allyl Isothiocyanate	C_4H_5NS	18°	17.5	8		0.67 CP @ 25°C	Surf. Tens. 34.5 dyn/cm @ 20°C; bp 152°C
99	Acetic anydride	$C_4H_6O_3$	0° 20°	22.5 20.5	8	C_p = 45.37 μ = 2.8	0.852 CP @ 24.1°C	Surf. Tens. 32.7 dyn/cm @ 20°C; fp -73.1°C; bp 139.9°C
100	Methylethyl Ketone (2 - butanene)	C_4H_8O	23° 79.0° BP	18.4 14.4	8	C_p = 39.68 μ = 2.7	0.417 CP @ 21.3°C	Surf. Tens. 24.6 dyn/cm @20°C; mp -86.4°C; bp 79.6°C
101	Ethyl Acetate	$C_4H_8O_2$	20°	6.4	8		0.44 CP @ 21.3°C	(see #7)
102	Methyl Propionate	$C_4H_8O_2$	19°	5.4	8		0.47 CP @ 16.79°C	Surf. Tens. 24.9 dyn/cm @ 20°C; mp -87°C; bp 78°C; flashpoint -2°C
103	Propyl Formate	$C_4H_8O_2$	23°	9.1	8	C_p = 42.7 μ = 1.893	0.546 CP @ 15.5°C	Surf. Tens. 24.5 dyn/cm @ 20°C; flash point -3°; mp -93°C; bp 81°
104	Isobutyl Bromide (1-Bromo-2-methyl propane)	C_4H_9Br	20.7°	6.6	8		0.611 CP @ 23.7°C	Misc. with alcohol; mp -119°C; bp 91.5°C
105	Isobutyl Chloride (1-chloro-2-methylpropane)	C_4H_9Cl	14°	7.1	8	C_p = 41.75 μ = 2.04	0.4637 CP @ 18.69°	Surf. Tens. 21.97 dyn/cm @ 20°C; mp -131°C; bp 68°C
106	Isobutyl Iodide (1- odo-2-methylpropane)	C_4H_9I	20°	5.8	8		0.84 CP @ 22°C	Surf. tens. 17.9 dyn/cm @ 119.5°C.; mp -93°C; bp 120°C
107	n-Butyl Alcohol	$C_4H_{10}O$	25° 117.7° BP	17.8 8.1	8		2.80 CP @ 21.8°	Surf. Tens. 24.6 dyn/cm @ 20°C; fp -19°C; bp 117.7°C
108	Isobutyl Alcohol 2-methyl-1-propanol	$C_4H_{10}O$	-50° 0° 20°	27.0 20.5 18.7	8	C_p = 43.85 μ = 1.79	3.978 CP @19°C	Surf. Tens. 23 dyn/cm @ 20°C; mp -108°C; bp 107°C; flashpoint 82°F

(10)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data	
109	n-Butylamine	$C_4H_{11}N$	21°	5.3 @ 3.6x 10^8 Hz	8	μ = 1.4	0.68 CP @25°C	Surf. Tens. 19.7 dyn/cm @ 41°C	fp -49.1°C bp 77.1°C
110	Pyridine	C_5H_5N	20° 80°	12.5 10.6	8	C_p = 32.4 μ = 2.2@17°	0.945 CP @ 20°C	Surf. Tens. 38.0 dyn/cm @20°C flashpoint 74°F	mp -42°C bp 115.5°C
111	Diethyl Ketone (dimethyl acetone)	$C_5H_{10}O$	15°	17.3	8		0.4748 CP @ 18.7°C	Surf. tens. 25.3 dyn/cm @ 15°C.	mp -42°C bp 101°C
112	Methyl propyl Ketone (Ethyl Acetone)	$C_5H_{10}O$	15°	16.8	8		0.5109 CP @ 18.3°C	flashpoint 12°C	mp -78°C bp 101.7°C
113	Ethyl Propionate	$C_5H_{10}O_2$	20°	5.7	8	C_p = 50.45 μ = 1.742	0.53 CP @ 20°C	Surf. tens. 24.3 dyn/cm @ 20°C	mp -73°C bp 99°C
114	Propyl Acetate	$C_5H_{10}O_2$	20°	6.3	8		0.57 CP @ 20°C	Surf. Tens. 24.3 dyn/cm @ 20°C flash pt. 14°C	mp -92°C bp 96°C
115	Piperidine	$C_5H_{11}N$	20°	5.9	8		1.37 CP @ 25°C	strong base	mp -7° bp 106°
116	Pentane	C_5H_{12}	0° 20° 60°	18.3 15.8 11.2	8		0.235 CP @ 18.9°		fp -129.7°C bp 36°C
117	Isoamyl alcohol (isobutyl corbinol)	$C_5H_{12}O$	23° 80°	15.3 8.8	8	C_p = 50.24 μ - 1.82	3.86 CP @ 23.8°	Surf. tens. 23.8 dyn/cm @ 20°C. flash pt. 114°C	mp -117.2°C bp 132°C
118	Bromobenzene (phenyl bromide)	C_6H_5B	13° 20°	5.4 5.4	8	C_p = 34.77 μ = 1.73	1.17 CP @ 18.2°	Surf. Tens. 36.5 dyn/cm @ 20°C flash pt. 51°C	fp -30.6°C bp 156°C
119	Chlorobenzene	C_6H_5Cl	13° 20°	5.6 5.8	8		0.80 CP @ 20.1°	(see #12)	
120	O-Chlorophenol	C_6H_5ClO	19°	8.2	8		4.21 CP @ 20°	dangerous	fp 7°C bp 175°C

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
	Nitrobenzene	$C_6H_5NO_2$	-10° 0° 102	9.9 39.7 32.3	8		2.01 CP @ 20°C	(see #34)
122	m-Chloroaniline	C_6H_6ClN	16°	13.3	8		3.50 CP @ 25°C	poisonous fp -10.6°C bp 228°C
	Aniline	C_6H_7N	0° 20° 50°	7.7 7.2 6.5	8 8		4.84 CP @ 17.28°	(see #60) mp -6.2°
124	α - Picoline	C_6H_7N	20°	10.0	8		0.79 CP @ 25°	Surf. tens. 31.3 dyn/cm @ 46°C. mp -69.9°C bp 129°C
125	Phenylhydrazine	$C_6H_8N_2$	23°	7.1	8		4.58 CP @ 50°	Surf. Tens. 46.1 dyn/cm @ 20°C poisonous mp 19.3°C bp 243.5°C
126	Cyclohexanone	$C_6H_{10}O$	20° -40°	18.2 19.9	8 10		2.30 CP @ 17.3°	Vapor press 136 mm @ 212°F flash pt. 128°F fp -47°C bp 156.7°C
127	Mesityl Oxide	$C_6H_{10}O$	20°	15.4	8		0.87 CP @ 251C	Surf. tens. 28.3 dyn/cm @ 24°C flash pt. 90°F fp -46.4°C bp 130°C
128	Propionic anhydride	$C_6H_{10}O_3$	16°	18.3 @5x10^{8}Hz	8		1.22 CP @ 14.7°C	Surf tens. 30.3 dyn/cm @ 20°C. flash pt. 165°F mp -45°C bp 167°C
129	Ethyl acetoacetate	$C_6H_{10}O_3$	22°	15.9	8		1.712 CP @ 20°C	Surf. Tens. 32.51 dyn/cm @ 20°C flash pt. 185°F mp -80°C bp 180 C
130	Diethyl oxalate	$C_6H_{10}O_4$	21°	8.2	8	C_p = 63.29 μ = 2.49	1.76 CP @ 25°C	Surf. Tens. 32.0 dyn/cm @ 20°C flash pt. 168°F mp - 40.6°C bp 186°C
131	Cyclohexanol	$C_6H_{12}O$	26° 100°	15.0 7.2	8		20.3 CP @ 39°C	flash pt. 68°C mp 23°C bp 160.9°C
132	Amyl Formate	$C_6H_{12}O_2$	15° 19°	7.7 5.7	8		0.794 CP @ 20°C	Solv. for cellulose esters. flash pt. 80°F bp 123.5°C

(12)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
133	Ethyl Butyrate	$C_6H_{12}O_2$	20°	5.1	8		0.66 CP @ 20°C	Surf. tens. 23.2 dyn/cm @ 20°C; mp -93°C bp 120.6°C
134	Paraldehyde	$C_6H_{12}O_3$	20° 128°	14.5 6.29	8 10		1.31 CP @ 15°C	mp 12.6°C; flash pt. 111.2°F bp 124.5°C
135	Benzotrichloride	$C_7H_5Cl_3$	20°	7.4	8		3.07 CP @ 10°C	mp -5°C bp 213°C
136	Benzonitrite	C_7H_5N	0° 20°	28.8 26.5	8		1.25 CP @ 25°C	very toxic; mp -13.1°C bp 190.7°C
137	Phenyl isocyanate (phenyl carbinide)	C_7H_5NO	17° 20°	5.7 8.9	8		1.33 CP @ 20°C	bp 165°C
138	Phenyl isothiocynate (phenyl mustard oil)	C_7H_5NS	20°	10.7	8		1.4 CP @ 25°C	mp -21°C bp 221°C
139	Benzaldehyde	C_7H_6O	0° 20°	20.0 18.0	8		1.40 CP @ 25°C	Surf. Temp 40.04 dyn/cm @ 20°C; mp -26°C bp 179.9°C
140	Salicylaldehyde	$C_7H_6O_2$	15° 20°	19.2 20	8		1.798 CP @ 45°	mp -7°C bp 196°C
141	Benzyl Alcohol	C_7H_8O	0° 20° 50°	15.9 13.0 10.3	8		5.58 CP @20°C	Surf. Tens. 39.0 dyn/cm @ 20°C flash pt. 96°C; bp 206°C mp -15.3°C
142	O-Cresol	C_7H_8O	24° 40°	5.8 8	8		9.56 CP @ 20°C	mp 30.4°C bp 191°C
143	m-Cresol	C_7H_8O	24° 40°	5.0 8	8		16.9 CP @ 20°	mp 10.7°C bp 202°C; flashpoint 86°C
144	p-Cresol	C_7H_8O	24° 40°	5.6 13	8		18.9 CP @ 20°C	mp 34°C bp 202°C

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
145	Methylaniline	C_7H_9N	0° 20°	7.9 6.0	8		2.303 CP @ 20°C	Surf. tens. 39.6 dyn/cm @ 20°C mp -57°C bp 190°C
146	O-Toluidine	C_7H_9N	20° 58°	6.0 5.71	8 10		4.39 CP @20°	Surf. tens. 40 dyn/cm @20°C flash pt. 87°C mp -21°C bp 200°C
147	m-Toluidine (3-Aminotoluene)	C_7H_9N	20° 58°	6.0 5.45	8	C_p = 51.84 μ = 1.45	3.31 CP @ 25°	Surf. Tens. 36.9 dyn/cm @ 20°C mp - 31.5°C bp 203°C
148	Diethyl malonate (ethylmalonate)	$C_7H_{12}O_4$	21°	7.9	8	C_p = 72.1 μ = 2.54	1.88 CP @ 25°	Surf. tens 31.7 dyn/cm @ 20°C. mp -50°C bp 198°C
149	Dipropyl Ketone (butyrone)	$C_7H_{14}O$	17°	12.6	8		0.685 CP @ 25°	Surface Tension 25.2 dyn/cm @ 25°C flash pt. 49°C mp -32.1°C bp 143.7°C
150	Amyl acetate (banana oil)	$C_7H_{14}O_2$	20°	5.0	8		1.58 CP 25°C	flash pt. 77°F n-amylacetate mp -70.8°C bp 148°C
151	Heptyl alcohol (1-heptanol)	$C_7H_{16}O$	21°	6.7	8		7.0 CP @ 20°	mp -34°C bp 173°C
152	Benzyl cyanide	C_7H_7N	0° 20° 50°	20.1 18.3 16.8	8		1.98 CP @ 25°	mp -24°C bp 233°C
153	Acetophenone	C_8H_8O	15° 50°	18.6 15.9	8		1.99 CP 16°C	flash pt. 180°F fp 19.7°C bp 201.7°C
154	Methyl benzoate (niobe oil)	$C_8H_8O_2$	20°	6.9	8		2.067 CP @ 20°	mp -12.3°C bp 198.6°C
155	Phenyl acetate (acetyl phenol)	$C_8H_8O_2$	20°	5.3	8		1.83 CP @ 45°	bp 195°C
156	Ethylaniline	$C_8H_{11}N$	0° 20°	6.3 5.9	8		2.98 CP @ 10°	Surf. Tens. 36.6 dyn/cm @ 20°C mp -63.5°C bp 206°C

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No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data	
	Guinoline (Icuitol)	C_9H_7N	25° 238°	9 5.0	8		3.64 CP @ 20°C	(see #38)	
158	Benzyl Acetate (benzoic ether)	$C_9H_{10}O_2$	21°	5.0	8	C_p = 36.79 μ = 1.8	1.423 CP @ 45°	Solv't for cellulose flash pt. 102°C	bp 212°C mp = 51°C
159	Ethyl benzoate	$C_9H_{10}O_2$	20°	6.0	8	C_p = 57.8 μ = 1.99	2.238 CP @ 20°	*Surf. Tens. 35.5 dyn/cm* @ 20°C	*mp -32.7°C* bp 212.9°C
160	Ethyl Salicylate (salicylic ether)	$C_9H_{10}O_3$	21°	8.4	8		1.803 CP @ 45°	Surf. Tens. 38.30 dyn/cm @ 20.5°C	mp 1°C bp 231°C
161	Ethyl Phenylacetate (d-toluic acid ethyl ester)	$C_{10}H_{12}O_2$	21°	5.4	8		2.39 CP @ 25°		bp 276°C (bp 226°C)
162	Carvol di form (carvone)	$C_{10}H_{14}O$	18°	11.2	8		3.39 CP @ 25°	Surf. *tens. 15.6 dyn/cm* @ 227.5°C.	*bp 230°C*
163	Menthone	$C_{10}H_{18}O$	18°	8.9	8		2.31 CP 25°C		mp -6°C bp 207°C
164	Triethyl aconitate	$C_{12}H_{18}O_6$	20° 70	6.4 5.5	8		11.7 CP @ 25°C	Surf. tens. 34.55dyn/cm @ 20.3°C. (plasticizer)	bp 154°C @ 5 mm
165	Deuterium oxide (heavy water)	D_2O	25°	78.2	10			Inorganic liquid	*mp 3.8°C* bp 101.4°C
166	Hydrogen Peroxide	H_2O_2	0°	84.2	10			Inorganic Surf. Tens. 76.1 dyn/cm @ 18.2°C strong oxidant)	mp -2°C bp 158°C
167	Ammonia	NH_3	-33° 5° 35°	22.4 18.9 16.3	10		0.317 CP @-50°C	Inorganic Surf. Tens. 18.1 dyn/cm @ 34.1°C	fp -77.7°C bp -33.5°C
168	Nitrosyl Bromide	NOBr	15°	13.4	10			Inorganic	mp -55°C

(15)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
169	**Nitrosyl Chloride**	NOCl	12°	18.2	10			Inorganic bp -5.5°C Oxidizing agent, c orrosive, poisonous
170	**Hydrazine**	N_2F_4	20°	52.9	10		1.29 CP @ 1°C	Surf. Tens. 91.5 dyn/cm @ 25°C mp 2°C Inorganic scavenger for oxygen bp 113.5°C (reducing agent) flash pt. 126°F
171	**Phosphoryl Chloride (phosphorous oxychloride)**	$POCl_3$	22°	13.3	10			Inorganic mp 1.25°C (corrosive liquid) bp 107.2°C Surf. tens. 21.1 dyn/cm @ 125°C
172	**Thiophosphoryl Chloride**	$PSCl_3$	22°	5.8	10			Inorganic mp -35°C (corrosive liquid) bp 126°C
173	**Thionyl Bromide**	$SOBr_2$	20°	9.06	10			Inorganic fp -52°C bp 138°C
174	**Thionyl Chloride (sulfur oxychloride)**	$SOCl_2$	20°	9.25	10			Inorganic mp -105°C bp 78.8°C
175	**Sulfur dioxide**	SO_2	-20 0 20	17.6 15.0 14.1	10		.55 CP @ -33.5°	Inorganic mp -76°C bp -10°C
176	**Sulfuryl Chloride**	SO_2Cl_2	22°	10.0	10			Inorganic mp -64°C (corrosive liquid) bp 69°C
177	**Hydrocyanic acid (hydrogen cyanide)**	CHN	0° 20°	158.1 114.9	10			fp -13.3°C poisonous, flash pt. 0°C bp 25.6°C
178	**Dibromomethane (methylene bromide)**	CH_2Br_2	10° 40°	7.77 6.68	10			solidifies -52°C bp 97°C
	Dichloromethane (methylene chloride)	CH_2Cl_2	20°	9.08	10			(also see #1) mp -97°C bp 40°C
180	**Diiodomethane (methylene iodide)**	CH_2I_2	25°	5.32	10			Surf. Tens. 50.76 dyn/cm @ 20°C mp -66°C bp 42°C

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No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data	
	Formic Acid	CH_2O_2	16°	58.5	10		2.38 CP @ 7.59°C	(also see #63)	
182	Bromomethane (methyl bromide)	CH_3Br	0°	9.82	10			poisonous	mp -84°C bp 4.6°C
183	Chloromethane (methyl chloride)	CH_3Cl	-20°	12.6	10			Surf. Tens. 16.2 dyn/cm @ 20°C	mp - 97.6°C bp 23.7°C
184	Iodomethane (methyl iodide)	CH_3I	20°	7.0	10	$C_p = 0.2079 + 2.5x10^{-4}t$ $\mu = 1.35$	0.518 CP @ 15°C.	Surf. Tens. 25.8 dyn/cm @ 20°C	mp -66°C bp 42°C
185	Formamide (methanamide)	CH_3NO	20°	109	10		7.55 CP @ 0° 3.3 CP @ 25°	Surf. Tens. 58.2 dyn/cm @ 20°C (good solvent)	mp 2.5°C bp 200°C
	Methanol (wood alcohol)	CHyO	25° -20°	32.6 40	10			(also see #51)	
187	Methylamine	CH_5N	-10° 25°	11.4 9.4	10			Surf. Tens. 22.2 dyn/cm @ -12°C (GAS ?)	mp -92.5°C bp -6.79
188	1,1,2,2-Tetrabromo-ethane	$C_2H_2Br_4$	3° 22°	8.6 7.0	10			Surf. Tens. 49.67 dyn/cm @ 20°C	mp 0.1°C bp 239°C
189	Dichloroacetic acid (Urners liquid)	$C_2H_2Cl_2O_2$	22° 61°	8.2 7.8	10			Surf. Tens. 35.4 dyn/cm @ 25.7°C (corrosive liquid)	mp -4°C bp 193°C
190	Acetyl chloride	C_2H_3ClO	2° 22°	16.9 15.8	10			Surf. Tens. 26.7 dyn/cm @ 14.9°C (corrosive liquid)	mp -112°C bp 51°C
191	Chloroacetic acid	$C_2H_3ClO_2$	60°	12.3	10			Surf. Tens. 35.4 dyn/cm @ 25.7°C	mp 61°C bp 185°C
192	Ethylene oxide	C_2H_4O	-1°	13.9	10		0.57 CP @ -49.8°C	Surf. Tens. 24.3 dyn/cm @ 20°C flash pt. <-4°F	mp -111°C bp 10.7°C

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
	Acetaldehyde	C_2H_4O	10°	21.8	10		0.279 CP @0°C	(see #72)
194	Acetic Acid	$C_2H_4O_2$	20° 40° 70°	6.15 6.29 6.62	10		1.31 CP @ 15°C	Surf. Tens. 27.8 dyn/cm @ 20°C; mp 16.6°C bp 118°C
	Methyl Formate	C_2HyO_2	20°	8.5	10			(see #74)
196	2-Chloroethanol (Ethylene chlorohydrin)	C_2H_5ClO	25° 132°	25.8	10	μ = 1.74	3.913 CP @ 15°C.	poisonous; flash pt. 140°F; mp -69°C bp 128°C
197	Acetamide	C_2H_5NO	83°	59	10			mp 82°C bp 223°C
198	Nitroethane	$C_2H_5NO_2$	30°	28.0	10	μ = 3.19	0.661 CP @ 25°C.	Surf. Tens. 32.2 dyn/cm @ 20°C flash pt. 106°F; fp -90°C bp 114°C
199	Ethanol	C_2H_6O	25° -60°	24.3 41.0	10			(see #52)
200	Glycol	$C_2H_6O_2$	25°	37.7	10			(see #55)
201	Dimethylamine	C_2H_7N	0° 25°	6.32 5.26	10			Gas at ord. temp.; mp -92°C bp 6.8°C
202	2-Propen-1ol Acetone (Allyl Alcohol)	C_3H_6O	15° 25° 56°	21.6 20.7 17.7	10		2.145 CP @ 0°C	(see #65)
203	Propionaldehyde	C_3H_6O	17°	18.5	10			(see #88)
204	Ethyl Formate	$C_3H_6O_2$	25°	7.1	10		0.40 CP @ 20°	(see #90)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
205	Methyl Acetate	$C_3H_6O_2$	25°	6.68	10		0.48 CP @ 0°C	(see #91)
206	dl-Lactic Acid	$C_3H_6O_3$	17°	22	10			(see #92)
207	Ethyl Carbamate (Urethan)	$C_3H_7NO_2$	50°	14.2	10		0.868 CP @ 15°C	mp 49°C bp 180°C
208	1-Propanol (propyl alcohol)	C_3H_8O	-80 -34 25	38 24 20.1	10			(see #95)
209	2-Propanol	C_3H_8O	25	18.3	10			(see #96)
210	1,2-Propanediol (propylene glycol)	$C_3H_8O_2$	20°	32.0	10			Surf. Tens. 40.1 dyn/cm @ 25°C (plasticizer) bp 188°C flash pt. 99°C
211	1,3-Propanediol	$C_3H_8O_2$	20°	35.0	10	$\mu = 2.5$		bp 210°C
212	Glycerol (glycol alcohol)	$C_3H_8O_3$	25°	42.5	10			Surf. Tens. 63.4 dyn/cm @ 20°C mp 17°C bp 290°C
213	Isopropylamine	$C_3H\ N$	20°	5.5	10			(see #97)
214	Maleic Anhydride (2,5-forandiane)	$C_4H_2O_3$	60°	50	10			(plasticizer) mp 53°C bp 200°C
	Allyl isothiocyanate	C_4H_5NS	18°	17.2	10			(see #98)
	Acetic anhydride	$C_4H_6O_3$	1° 19°	22.4 20.7	10			(see #99)

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No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
217	2-Butanone (sec-buty alcohol)	C_4H_8O	20°	18.5	10	C_p = 39.58 μ = 2.747	0.423 C_p @ 15°C.	Surf. Tens. 23.5 dyn/cm @ 10°C flash pt. 75°F mp -114.7°C bp 99.5°C
218	Butyraldehyde (n-butyl aldehyde)	C_4H_8O	26° 77°	13.4 10.8	10		4.3 poise 20°C	Vaq Press 91.5 mm @ 20°C flash pt. 20°F fp -99°C bp 75.7°C
	Propyl formate	$C_4H_8O_2$	19°	7.7	10			(see #103)
	Ethyl Acetate	$C_4H_8O_2$	25° 77°	6.02 5.3	10		0.582 CP @ 0°	(see #7)
	Methyl propionate	$C_4H_8O_2$	19°	5.5	10			(see #102)
222	Morpholine	C_4H_9NO	25°	7.33	10		2.23 CP @ 20°	flash pt. 100°F mp -4.9°C bp 128.9°C
	1-Butanol (n-butyl alcohol)	$C_4H_{10}O$	20° 25° 118°	17.8 17.1 8.2	10			(see #107)
	2-Methyl-1-propanol (isobutyl alcohol)	$C_4H_{10}O$	25° -34° -80°	17.7 26 34	10			(see #108)
225	2-Butanol (sec-butyl alcohol)	$C_4H_{10}O$	25°	15.8	10		4.21 C_p @ 20°C.	flash pt. 75°F mp -114.7°C bp 99.5°C
226	2-Methyl-2-propanol (tert-butyl alcohol)	$C_4H_{10}O$	30° 50° 70°	10.9 8.49 6.89	10			mp 25.5°C bp 82.9°C flash pt. 52°F
227	Furfural (ant oil)	C_5HyO_2	1° 20°	46.9 41.9	10		2.48 CP @0°C	Surface Tens. 43.5 dyn/cm @ 20°C mp -36.5°C bp 161°C wetting agent flash pt. 150°F
	Pyridine	C_5H_5N	25° 116°	12.3 9.4	10		0.974 CP @ 20°C	(see #110)

(20)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
229	2,4-Pentanedione (acetylacetone)	$C_5H_8O_2$	20°	25.7	10		0.0058 poise @ 20°C	fp -23.5°C bp 140.5°C
230	2-Pentanone (methyl propyl ketone)	$C_5H_{10}O$	20° 160°	15.4 22.0	10			(see #112)
231	3-Pentanone (diethyl ketone)	$C_5H_{10}O$	20° -20° -40°	17.0 19.4 19.8	10			(see #111)
232	Methyl Butyrate	$C_5H_{10}O_2$	20°	5.6	10			flash pt. 14° mp -95° bp 102°C
233	Piperdine	$C_5H_{11}N$	22°	5.8	10			(see #115)
234	1-Pentanol (n-amyl alcohol)	$C_5H_{12}O$	25°	13.9	10	$C_p = 48.2$ $\mu = 1.8$		flash pt. 135°F fp -78.9°C bp 137.8°C
235	3-Methyl-1-butanol (isobutyl carbinol)	$C_5H_{12}O$	25° 132°	14.7 5.8	10			(see #117)
236	2-Methyl-2-butanol (tert-amyl alcohol)	$C_5H_{12}O$	25°	5.82	10			flash pt. 70°C fp -11.9°C bp 101.8°C
237	O-dichlorobenzene (1,2 dichlorobenzene)	$C_6H_4Cl_2$	25°	9.93	10			heat transfer fluid flash pt. 77°C fp -20°C bp 172°C
238	m-dichlorobenzene (1,3 dichlorobenzene	$C_6H_4Cl_2$	25°	5.04	10			mp -24°C bp 172°C
239	Bromobenzene	C_6H_5Br	28°	5.40	10		1.196 CP @ 15°C	(see #118)
240	Chlorobenzene	C_6H_5Cl	-50° -20° 25°	7.28 6.30 5.62	10		0.90 CP @ 15°C	(see #12)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
241	O-chlorophenol	C_6H_5ClO	25°	6.31	10		4.11 CP @ 25°C	(see #120)
242	p-Chlorophenol	C_6H_5ClO	55°	9.47	10		4.99 CP @ 50°C	mp 42°C bp 217°C
243	Nitrobenzene	$C_6H_5NO_2$	25° 90°	34.82 24.9	10		2.91 CP @ 2.95°C	(see #34)
244	O-Nitrophenol	$C_6H_5NO_3$	50°	17.3	10			mp 44°C bp 214°C
245	m-Bromoaniline	C_6H_6BrN	19°	13.0	10		6.81 CP @ 20°C	
246	m-Chloroaniline	C_6H_6ClN	19°	13.4	10			(see #122)
247	O-Nitroaniline	$C_6H_6N_2O_2$	90°	34.5	10			
248	p-Nitroaniline	$C_6H_6N_2O_2$	160°	56.3	10			mp 148°C
249	Phenol (carbolic acid)	C_6H_6O	60°	9.78	10		12.7 CP @ 18.3°C	strong corrosive poison mp 42°C bp 182°C
250	Butyl Acetate (butyl ethanoate)	$C_6H_{12}O_2$	-73° 20°	6.8 5.0	10	C_p = 59.78 μ = 1.841	1.00 CP @ 0°C	Surf. tens. 25.2 dyn/cm. fp -75°C bp 126°C flash pt. 92°F
251	1-Hexanol (hexyl alcohol)	$C_6H_{14}O$	25° 75°	13.3 8.5	10	C_p = 55.56 @16.9°C	4.592 CP @ 25°C	mp -52°C bp 155°C flashpoint 137°F
252	Benzoyl Chloride	C_7H_5ClO	0° 20°	29 23	10			mp 0.5°C flash pt. 72°C bp 197°C

(22)

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
253	m-Bromotoluene	C_7H_7Br	58°	5.36				mp -39.8°C bp 183.7°C
254	p-Bromotoluene	C_7H_7Br	58°	5.49	10			mp 28.5°C bp 184.5°C
255	m-Chlorotoluene	C_7H_7Cl	20° 58°	5.55 5.04	10			fp -48.89°C bp 161.7°C
256	p-Chlorotoluene	C_7H_7Cl	20° 58°	6.08 5.55	10			fp 6.5°C bp 162°C
257	α - Chlorotoluene (benzyl chloride)	C_7H_7Cl	13°	7.0	10			Surf. tens. 19.5 dyn/cm @ 175.5°C. (corrosive liquid) mp -43°C bp 179°C
258	O-Nitrotoluene (nitrotoluol)	$C_7H_7NO_2$	20° 58°	27.4 21.6	10			mp -9.5°C bp 222°C
259	m-Nitrotoluene	$C_7H_7NO_2$	20° 58°	23.8 21.9	10			mp 16°C bp 230°C
260	p-Nitrotoluene	$C_7H_7NO_2$	58°	22.2	10			mp 51.4°C bp 237°C
	N-Methylaniline	C_7H_9N	22°	5.97	10			(see #145)
262	Methyl salicylate	$C_8H_8O_3$	30°	9.41	10			Surf. Tens. 31.9 dyn/cm @ 94°C mp -8.3°C bp 222°C
263	1-Octanol (actyl alcohol)	$C_8H_{18}O$	20°	10.3	10			(antifoaming agent) mp -16°C bp 194°C
264	Isoquinoline	C_9H_7N	25°	10.7	10		3.57 CP @ 25°C	mp 23°C bp 243°C

No.	Name	Formula	Temp °C	Dielect. Const.	Ref.	Dielect. Strength	Viscosity	Other Data
265	Cinnamaldehyde (cinnamic aldehyde)	C_9H_8O	24°	16.9	10			mp -8°C bp 248°C
266	Dimethyl phtalate	$C_{10}H_{10}O_4$	24°	8.5	10			Vap. pres.<0.1 mm @ 20°C stable, plasticized bp 282°C mp 5.5°C flashpoint 300°F
267	1-Decanol (n-decyl alcohol)	$C_{10}H_{22}O$	20°	8.1	10			Plasticized, antifoam Flash pt. 180°F mp 6°C bp 233°C
268	Benzophenone (diphenyl betone)	$C_{13}H_{10}O$	50°	11.4	10		4.79 CP @ 55°C	Crystals at room temp. Surf. tens. 45.1 dyn/cm @ 20°C. mp 48.5°C bp 30.5°C
269	Monopalmitin	$C_{19}H_{38}O_4$	67° 80°	5.34 5.09	10			mp 77°C
270	Tricresoyl Phosphate	$C_{21}H_{21}O_4P$	40°	6.9	10			Plasticized Stable, nonvolatile Crystallizes @ -35°C bp 420°C
271	Chloroform (trichloro methane)	$CHCl_3$	60° 21°	6.76 4.806				Surf. tens. 27.14 dyn/cm@ 20°C. flash pt. none fp -63.5°C bp
272	Diphenyl ether (diphenyl oxide)	$(C_6H_5)_2O$	0° 25°	7.7 7.0				Heat trans. med. mp 28°C bp 259°C flashpoint 115°C.

APPENDIX B

PROPERTIES OF DIALLYL PHTHALATE MONOMER

The following table has been extracted from the manufacturer's brochure (FMC Corporation) on Diallyl Phthalate monomer.

Diallyl Phthalate Monomer

Formula	$C_6H_4(COOCH_2CH\ CH_2)_2$ 246 MW
Specifications	
Specific gravity @ 20°C/20°C	1.117–1.123
Solubility in methanol	1 cc in 5 cc,clear—only slightly turbid
Acidity as acetic acid, %	0.1 max
Moisture (Karl Fischer), %	0.1 max
Color APHA Pt-Co	90 max
Odor	mild, slightly lachrymatory
Average properties	
Boiling range @ 4 mm*, °C	157–165
Mid-boiling point @ 4 mm, °C	161
Freezing point, °C	−70 (viscous liquid)
Pour point, °C	−59
Flash point (open cup), °F	330 (166°C)
Fire point, °F	359 (182°C)
Refractive index @ 25°C	1.516–1.520
Hydrolysis, acid number	1.0
Viscosity @ 20°C, centipoises	12.0
Vapor pressure @ 150°C, mm Hg	2.4
@ 200°C, mm Hg	27.0
Surface tension @ 20°C, dynes/cm	39
Specific heat 50–150°C, cal per gm,per °C	0.50 average
Solubility in water	insoluble
in water @ 25°C, %	0.6
in gasoline @ 25°C, %	24
in mineral oil @ 25°C, %	2.4
General solubility	Insoluble or limited solubility in gasoline, mineral oil, glycerine, glycols, and some amines. Soluble in most other organic liquids.
Thermal expansion @ 10–40°C,per °C	0.00076
Weight per gal @ 20°C,lbs	9.33

*Diallyl phthalate should not be distilled at atmospheric pressure. The high temperature required may cause polymerization.

APPENDIX C

DEVELOPMENT OF A HIGH ENERGY DENSITY CAPACITOR FOR PLASMA THRUSTERS

By

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DEVELOPMENT OF A HIGH ENERGY DENSITY CAPACITOR FOR PLASMA THRUSTERS*

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Abstract

This paper discusses the development of long-life, high-energy-density capacitors intended for spacecrafts. These low-inductance, extended-foil capacitors have a discharge life exceeding 10^7 shots and an energy-density up to 40 J/lb., when operated at 2.2 kV charge voltage and with a peak current of 35 kA, reversal of 25%, and rep-rate below 1 Hz. The capacitors are paper-free and are composed principally of polyvinylidene fluoride film ("K-film"), aluminum foil and impregnant. The film is characterized by its high dielectric constant of about 10, which tends to preclude the use of typical impregnants. A literature survey of impregnant candidates was performed and several impregnants were tested. Silicone oil and MIPB (monoisopropol biphenyl) emerged as the best candidates for this application. Tests are described which evaluate 80 μF capacitors at various temperatures and under conditions of vacuum.

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Introduction

The application of electric pulse-power equipment to spacecrafts results in performance requirements which are especially stringent. One example of this is the use of pulsed plasma thrusters for control of satellite orientation. This application has resulted in the requirement for improved high-energy-density capacitors capable of long life and high reliability. Substantial progress in capacitor state-of-art has accrued from research on capacitors intended for plasma thrusters.

This paper describes a technology program performed by Maxwell which was directed at the development of capacitors capable of 10^7 discharges when operated at the energy density of 40 J/lb. As of this writing, tests are still in progress and, therefore, this paper is intended to report progress to date and present status. Based on extrapolations of the data now available, the requirements as listed in Table 1, are attainable at the required voltage. Uncertainty persists regarding capacitor reliability at 10^7 discharges and the influence of temperature on life.

The capacitors studied during this program are extended foil, cylindrical winding composed of aluminum foil and a dielectric film called K-film, manufactured by the Kureha Corp. These windings are installed in steel cases and impregnated with one of several dielectric fluids. In most conventional capacitors, thorough impregnation of the entire winding is promoted by use of a thin ($\lesssim$ 1 mil) sheet of paper (Kraft capacitor tissue) introduced between contiguous surfaces, in order to provide a wick. When paper is included in capacitors it is placed between layers of film because their extremely smooth surfaces can impede the impregnation process and, in many constructions, paper is also placed between foil and film.

One of the major objectives of this program was to avoid use of paper because capacitors which include paper have important disadvantages, especially when used with high dielectric constant films, such as "K-film," whose dielectric constant, k, exceeds that of the paper. In that case, paper increases the size and weight of the winding, which reduces energy density. Another disadvantage of paper is its increased vulnerability to damage from ionizing radiation which may occur in space. In summary, this program had the two-fold objective of (1) developing a long-life, high-energy-density capacitor with energy density (total stored energy/total mass of capacitor, including case) in the range of 40 J/lb with life of 10^7 discharges, and (2) attaining that goal in a paper-free, K-film capacitor.

To attain high-energy density in a paper-free capacitor, a film with high relative dielectric constant is an obvious advantage. For example, conventional films such as polypropylene or polyester have relative dielectric constants, k, in the range of 2 - 3. Conventionally used impregnants have dielectric constants in that range also. At equal stress, a film with dielectric constant of about 10 has over three times the energy density. However, prior to this program, it was unclear whether reliable, paper-free capacitors, which included a film whose k exceeded that of the impregnant could be successfully constructed. In part, the difficulty in thoroughly impregnating a paper-free capacitor was thought to pose a serious limitation. However, by adapting vacuum impregnation techniques which were previously employed in other types of paper-free capacitors, a thorough impregnation was in fact achieved.

In addition to questions about impregnation, the combination of a high-k-film and a low-k-impregnant is not, à priori, an acceptable construction because of the way in which the electrostatic field is distributed within the winding. In principle, when this construction is subjected to low voltage, as it is during the initial stage of charging, the stress is higher in the impregnant layer than in the dielectric film by the factor k_F/k_I. Then, as voltage is increased, corona and charge migration occur in the impregnant which in effect short-circuits the liquid. This process must transfer the nearly full capacitor voltage to the dielectric film. The redistributing of this voltage in constructions which employ high k films and low k impregnants had an unknown influence on capacitor life.

During this program the dielectric fluids which were tested all had k_I less than k_F. Life curves were generated which clarified the influence of dielectric constant on life. Based on extrapolations, silicone oil and MIPB, when used in a paper-free capacitor with K-film were found capable of meeting the goal of 10^7 shots at 2.2 kV.

Selection of Impregnants

The capacitor development program was divided into four tasks, as shown in Table 2. The first task was a computer-assisted literature survey in which liquids with certain specified physical properties were systematically tabulated. Among the key properties was dielectric constant; about 300 liquids were listed, all with $k > 5$. Other important physical properties were compared such as phase-change temperature, resistivity, vapor pressure and viscosity. Liquids with properties like those of cyanoethyl sucrose and castor oil were rejected because they tend to freeze at or above $\simeq$ -20°C, which approaches the lower limit of capacitor operation. In the process of accepting or rejecting liquids, intuition played an important part, e.g., liquids which may freeze or crystallize were rejected because a phase-change within the capacitor probably would result in premature failure due to creation of impregnant-free voids.

Numerous materials were listed which had high vapor pressure such as the organic solvents. These materials were rejected because they would require special handling in order to ensure adequate impregnation. Additional research in that area would have been required, although in a future program the difficulty in handling these materials may not be as serious a limitation. (High dielectric constant in organic liquids was frequently associated with high vapor pressure.)

The Aroclor impregnants which are among the environmentally restricted polychlorinated biphenyls (PCB) were listed but were not selected for testing during this program because of the difficulty in obtaining them and also, other candidates appeared equally attractive. Ethylene glycol and several high k (>30) aqueous solutions were considered but their resistivity was too low, being $\lesssim 10^7$ Ω-cm, whereas about 10^{10} Ω-cm is minimum for the low loss capacitors of present interest.

Also considered were the conventional liquid impregnants such as Tricresyl phosphate (TCP, k = 6.9) and Silicone Oil. Finally, a group of four liquids were selected, two with the relatively high k of about 7 or greater and two with low k, less than 3. These materials are shown in Table 3. The entire listing was not exhaustively studied to the point where all physical properties of each liquid were obtained and analyzed. Time limitations prevented so detailed a study. There may very well be a superior material which escaped selection because certain physical properties were grossly irregular compared to more common impregnants, its properties unknown or were difficult to unearth. The listing still serves as a source of ideas for new impregnants for future experiments.

Scaled Experiments

Setup

Discharge-life experiments were conducted on 6 μF capacitors impregnated with each of the four selected liquids. A test circuit was employed with series inductance and resistance which could be readily changed.

The test waveform in the 6 μF capacitors was established by reference to the requirements of the final 80 μF thruster capacitors. The test circuit is shown in Figure 1. The peak current of about 35 kA at 2.2 kV in the final 80 μF capacitor motivated the use of 2.6 kA at 2.2 kV in the 6 μF test capacitor to maintain the same current density at given voltage. For most scaled tests, charge voltage was in the 4 kV to 5.5 kV range. The circuit elements parameters were held constant as test voltage was varied; therefore, at 5 kV, for example, peak current was about 6 kA.

Also, as voltage was varied, the ringing period remained constant. Therefore, initial rate-of-change in current varied in proportion to charge voltage. In summary, as charge voltage in a test capacitor was increased in order to accelerate discharge-life, the electrical stress in the film, the peak current, and $\dot{I}$ increased in proportion. A typical discharge current and voltage waveform is shown in Figure 2. Capacitor charging time was controlled by means of a resistor placed in series with the power supply. In general, charging time was about one sec and discharge rep-rate was about one shot per 10 sec. This maintained a maximum case temperature of about 100°F.

Results

TCP

Experimental results on TCP are shown in Figure 3. That experiment shows a comparison of life vs. stress curves for three different combinations of film layers. The solid line connects the average high-pot failure voltage with the program goal of 2.2 kV at 10^7 shots. The slope of this line may be calculated; life is a function of voltage to the exponent α, as in the equation

$$L_g = L_1 (V_g/V_1)^{-\alpha}$$

Solving for α:

$$\alpha = \ln(L_g/L_1)/\ln(V_g/V_1)$$

for $L_g = 10^7$ at $V_g = 2.2$ kV

and $L_1 = 1$ at $V_1 = 6$ kV

$$\alpha = 16$$

To attain the goals the data points must fall to the right of the goal-curve. Small excursions from the goal-curve represent large changes in slope. For example, the data obtained with two, 12 micron films indicate α of about 50, although so large a slope was not consistently obtained, presumably due to statistical variations in the mean life curves.

Extrapolations to the 10^7 shot-life are made from the data taken in the ≈ 1 to 10^4 shot range. An important data point occurs at the obscissa (where shot-life = 1) because there, the high-pot failure voltage is plotted with the assumption the capacitor withstood only the one discharge. When failed due to high-pot, the capacitor does not actually discharge into a load but rather fails internally. It is known that capacitors which are charged near their high-pot failure voltage tend to have very low discharge-lives and this was shown during the program. The curve is so steep when connecting the high-pot failure points and discharge-life points taken at lower voltage that use of the high-pot failure voltage as a point which corresponds to a one-shot life is a reasonable approximation. Experience obtained during previous capacitor development programs confirms this.

DAP

Results from DAP, the liquid with the highest dielectric constant in the group, were disappointing. Figure 4 shows four points taken at 5 kV. The spread in discharge-life was generally larger than that of the other liquids and inspection of the failed capacitors indicated serious electrochemical activity was occurring. Severe foil dimpling and tearing was evident.

The resistivity of DAP was lower than that of the other candidates and this appeared to be related to impurities. Successive filtrations through Fuller's earth were required to raise the resistivity to the minimum acceptable value of $\approx 10^9$ Ωcm. On these grounds, DAP was rejected as a candidate impregnant.

DAP was originally thought to have high potential because of its high dielectric constant.

MIPB and Silicone Oil

Results of 6 μF tests conducted with MIPB and Silicone Oil indicated that of the four liquids originally selected, these two appeared to be superior, based on two observations.

1) In each of these two cases, the discharge life was closely grouped as shown in the typical plots of Figure 4. (This consistency is important for extrapolations from the mean life points to estimates of life at high reliability.)

2) Inspection of the failed capacitors indicated silicone oil was qualitatively the most compatible and MIPB, the second most compatible material tested. This observation was based on the extent of cracking and dimpling which the foils and films underwent. In no case could the judgment be rendered that the electrophysical effects caused the failures which were observed; i.e., there was no specific correlation between those areas of the pads in which severe electrophysical action occurred and where the breakdown occurred. However, it is believed in longer-life capacitors the gradual dimpling of the materials and separations of the foils would eventually lead to failure. On these grounds, silicone oil and MIPB were selected as the optimum candidates.

An additional experiment was conducted on a group of five 30 μF capacitors impregnated with silicone oil. This experiment was conducted with larger capacitors to provide insight into performance when capacitance is mid-range between 6 μF and the final 80 μF. The data is shown in a

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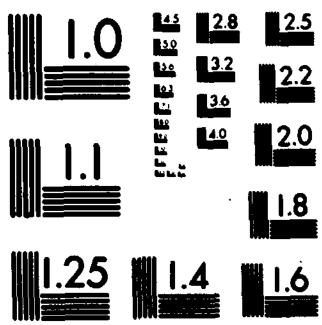

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Wiebull plot in Figure 5. The Wiebull plot provides estimates of reliability versus shot-life. For example, the plot indicates a characteristic life, η, of 8000 discharges (η corresponds to a reliability of 37%). If this were extrapolated to 2.2 kV by means of the equation:

$$L_2 = L_1 \, (V_2/V_1)^{-\alpha}$$

using α = 16, the slope of the goal-curve, the characteristic life would be 7.5 x 10^8 discharges. If the Wiebull plot were extended to the 99% reliability (1% failure) the life would be 330 discharges at 4.5 kV; at 2.2 kV this would provide 3 x 10^7 shot discharge life. Use of the slope of 16 is believed to be an underestimate based on the results to date. Higher values of slope would still further improve the reliability of these capacitors.

The sparcity of data results in wide confidence bands around the plotted reliability vs. discharge-life curve. Within the 90% confidence limits, lines which could be drawn to the left of the data would fall short of the 10^7-shot goal. Therefore, encouraging though this data is, more data points are required for confirmation.

Capacitor Can Manufacture

The final capacitors to be tested during this program will not themselves be used on spacecrafts. However, one group of these capacitors are undergoing accelerated life testing at 3.9 kV under vacuum with a resistive load which simulates the waveshape of the thruster except for the proportionately higher voltage, current, and $\dot{I}$. A second group of capacitors will undergo life testing in a plasma thruster. Therefore, the requirements of this program called for manufacture of full-scale, 80 μF capacitors in an appropriate case virtually identical to that required of a spacecraft.

Oil impregnated capacitors manufactured for use on spacecraft must be subjected to extremely stringent screening and quality control procedures to insure the best possible hermetic seal. The basic can is hydroformed from 40 mil 301 stainless steel sheet. Special tooling is used to insure dimensional accuracy of each can and minimum material thickness at any point on the can is 25 mils after forming. Cans not meeting dimensional requirements are rejected.

The can is chucked internally and a hole of appropriate diameter is cut in the center of the closed end of the can to accommodate the high voltage center stud brushing. A machined part consisting of the ground ring and mounting flange is vacuum brazed to the closed face of the can. The geometry of this part is such that the ground ring is concentric with the outer circumference to within .01 inches. The centerstud/bushing assembly is vacuum brazed to the can next. Special tooling is used to insure that the centerstud is perpendicular to the front face of the can to within ±1/2° and concentric with the ground ring within .01 inches. The resulting assembly is 100% helium leak tested at 1 x 10^{-9} Atm cc/sec.

The rear lids are especially machined and matched to each can within 5 mils on the diameter for a snug fit. The lid is designed in such a way as to flex without permanent distortion so that volumetric expansion due to temperature excursions can be accommodated. Thus, the capacitors are impregnated at the lowest temperature expected during operation so that the lids are unstressed when the can is sealed off. Internal expansion is taken up by deflection of the lid to insure that excessive pressure does not build up within the can at the maximum operating temperature.

The rear lid is welded to the can once the capacitor winding has been installed and the fill plug is soldered in place after impregnation. A redundant seal is formed around the centerstud/bushing and bushing/can braze joints by potting these areas with semirigid epoxy. The region around the fill plug is also redundantly sealed in this fashion. A machined metal ring is epoxied over the rear lid weld seam and a machined cap is epoxied over the tip of the centerstud to redundantly seal those areas. The techniques used in redundant sealing of the capacitors have been developed over the years as a result of experimentation using commercially available oil impregnated units. In some cases the "redundant" seals form the primary seals on commercial units.

Final Tests on 80 μF Capacitors

The first group of 80 μF capacitors tested at Maxwell and Fairchild delivered relatively poor results. This early group had large spread in discharge-life as shown in Table 4. After failure, these units were disassembled and it was concluded the winding tension was excessive. New windings were then prepared with reduced tension, and these comprise Group 2 in the table.

As of this writing tests on these Group 2 capacitors are being conducted. Although statistically meaningful data is not yet available, the data is encouraging. Two 80 μF capacitors were tested at Maxwell at 3.9 kV and failed after 1950 and 2080 discharges. (These tests were conducted at nominal room temperature and ambient pressure.)

This 2000 discharge-life would extrapolate to a characteristic life of 2 x 10^7 discharges, assuming a slope of -16. This life would be a most conservative estimate since the slope measured during the program was at least twice that value.

Another important factor is the reproducibility of failure-life, which may be emerging in this Group 2 data. Good reproducibility creates a steep Wiebull slope which results in high values of discharge-life at 99% reliability compared to the characteristic life. (A vertical line on the Wiebull plot occurs when all failures occur, at the same life; in that case, the characteristic life equals the life at 99% reliability.) In most cases to date, the characteristic life has been about one order of magnitude larger than the life at 99% reliability.

In addition to the Maxwell tests, a Group 2 capacitor is now undergoing 3.9 kV discharge-life tests at Fairchild under vacuum, at nominal room temperature. At this time, this capacitor has experienced 2,270 discharges and is still operating. Based on these preliminary results, it appears winding tension should be minimized with K-film capacitors

Additional testing at 3.9 kV is now being carried out both at Maxwell and at Fairchild. These tests will be followed by thruster life tests during which the capacitors will be operated at their rated voltage of 2.2 kV. This will confirm the discharge-life extrapolations discussed above.

Acknowledgement:

The authors wish to thank Mr. Robert Haug of Maxwell and Mr. Martin Brown of Fairchild for their support throughout this program.

TABLE 1

CAPACITOR SPECIFICATIONS AND GOALS

Energy	190 J at 2.2 kV
Voltage	2.2 kV ± 1%
Voltage Reversal	25%
Capacitance	80 μF + 10% - 5%
Inductance	15 nH (max)
Loss Factor	.01 Goal .013 (max at 25°C, 120 H)
Peak Current	35 kA
Initial dI/dt	10^{10} A sec^{-1}
Pulse Rate	0.17 Hz (normal) 1.0 Hz (max)
Burst Duration:	
at 0.17 Hz	Indefinite (assumed)
at 1.0 Hz	Not specified
Capacitor Temperature Range	-20°C to +50°C (design) -35°C to +70°C (goal)
Ambient Pressure	10^{-4} Torr
Radiation Environment	
Life	10^7 Shots
Reliability	Not specified
Gross Energy Density	40 J/lb (@2.2 kV)
Weight	4.75 lb.
Shape	Cylindrical
Dimensions	4.125 in. OD, 2.25 in. Length

TABLE 2

PROGRAM SUMMARY

1. Literature Survey - Primary object: List liquids with k > 5.
2. (a) Select four impregnants
   (b) Manufacture and test.
3. Manufacture final 80 μF capacitors.
4. Test final capacitors.

TABLE 3

IMPREGNANTS SELECTED FOR SCALED CAPACITOR TESTS

1.	TCP (Tricrosyl Phosphate)	k = 6.9
2.	MIPB (Monoisopropyl Biphenyl)	k = 2.5
3.	Silicone Oil	k = 3.6
4.	DAP (Diallyl Pthalate - monomer)	k ≥ 10

TABLE 4

80 μF CAPACITOR TESTS
AT 3.9 kV

	Maxwell (Ambient)	Fairchild (Vacuum)
Group 1	560, 1500, 5000	139, 231, on Charge
Group 2 (reduced tension)	1998, 2081	> 2300

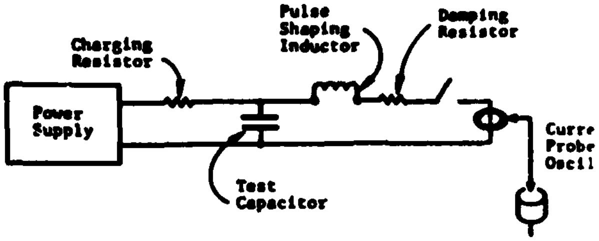

Figure 1. Test circuit for capacitor life tests.

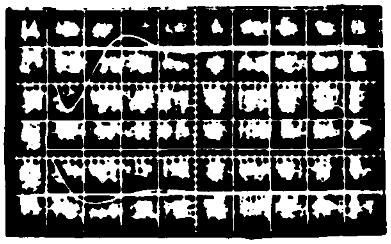

Figure 2. Typical current and voltage obtained from Peerson current probe (V_{chg} = 6 kV)

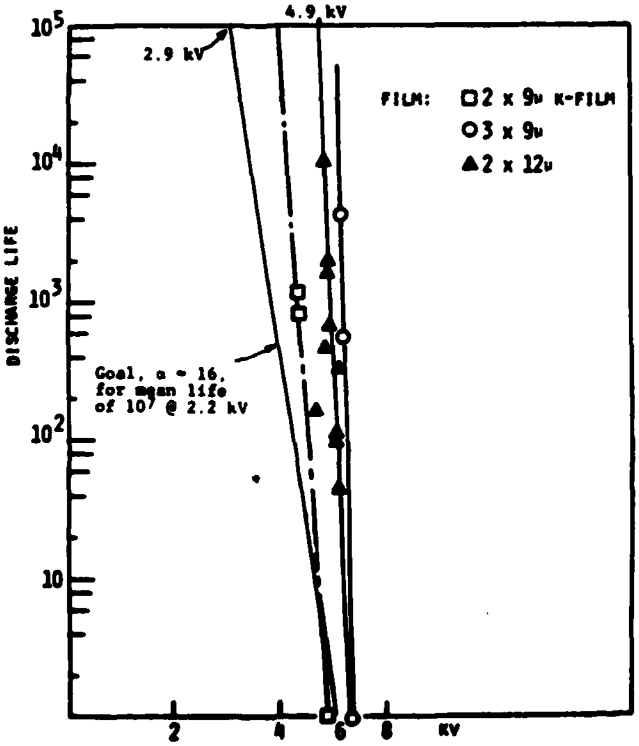

Figure 3. Shot-life versus charge voltage for 6 μF capacitors impregnated with TCP (tricresyl phosphate) with film thickness as a parameter

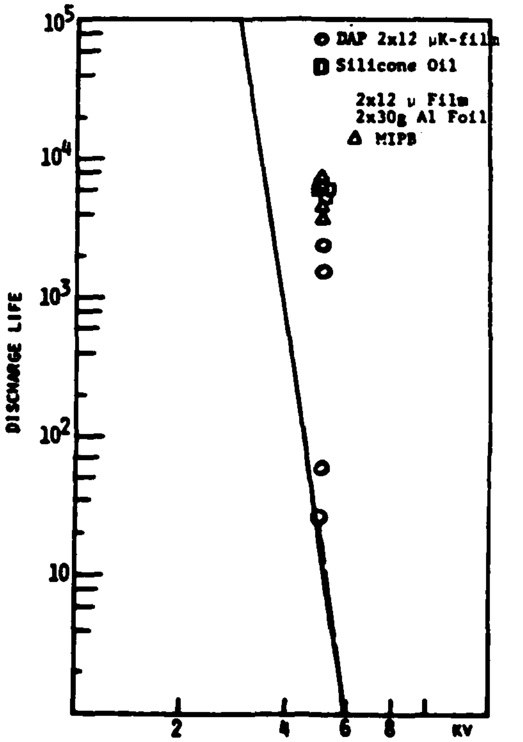

Figure 4. Shot-life versus charge voltage f
6 μF capacitors

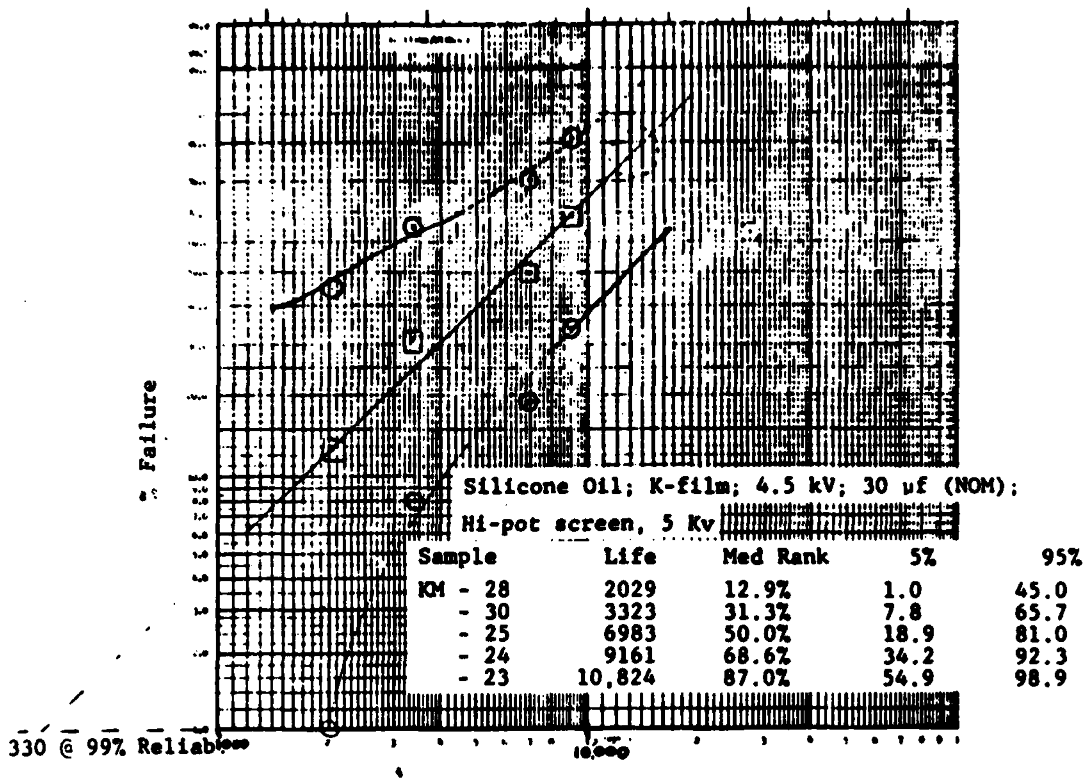

Figure 5. Wiebull plot of 30 µF K-film capacitors impregnated with silicone oil.